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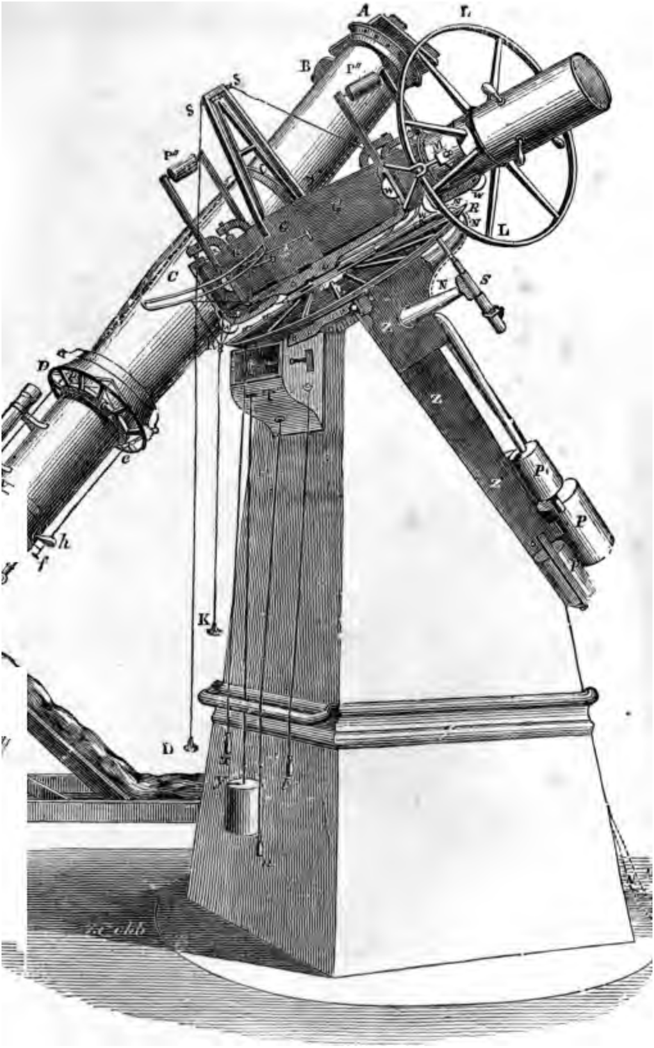


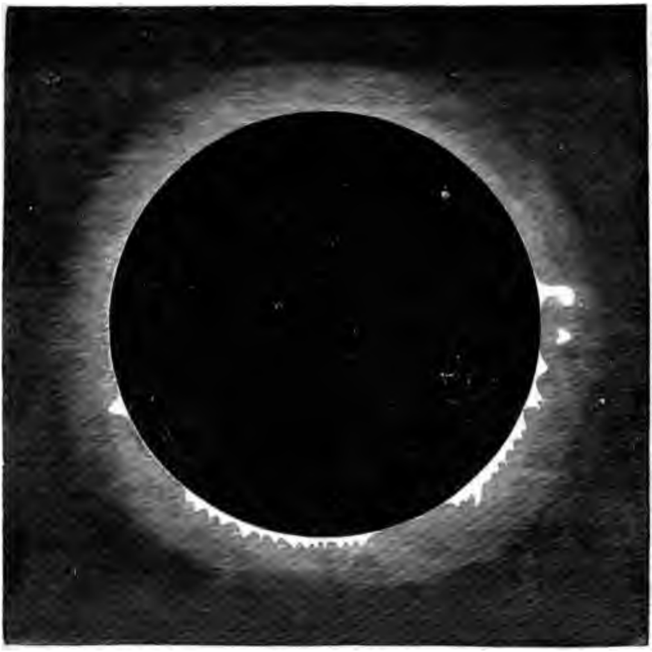
ew of the Oxford Heliometer, as given in Captain Smyth's "Ædes Hartwellianæ," or Description of Dr. Lee's Mansion at Hartwell, engraved from a drawing by Mrs. Smyth, and kindly put at the Publishers' disposal.

RUDIMENTARY ASTRONOMY

By the late Rev. ROBERT MAIN, M.A., F.R.S., F.R.A.S.
FORMERLY RADCLIFFE OBSERVER AT OXFORD

THIRD EDITION

REVISED AND CORRECTED TO THE PRESENT TIME BY
WILLIAM THYNNE LYNN, B.A., F.R.A.S.
FORMERLY OF THE ROYAL OBSERVATORY, GREENWICH



Solar Eclipse of 1851, July 28 (see p. 88).

LONDON
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STATIONERS' HALL COURT, LUDGATE HILL
1882.

ADVERTISEMENT TO THE THIRD EDITION.

The gifted Author of this useful little work was First Assistant at the Royal Observatory, Greenwich, from 1835 to 1860, and afterwards Radcliffe Observer at Oxford, where he died exactly four years ago, on the 9th of May, 1878. It was originally published in 1852 to form one of a series of Rudimentary Treatises on scientific subjects, the scheme being principally to describe clearly to those possessed of a small amount of mathematical knowledge the elementary principles of Astronomy as a science. It was revised by the Author for a Second Edition in 1869, when he also took the opportunity of adding an Appendix on the new and important branch of Spectrum Analysis. That Edition being now exhausted, I have been asked to prepare a Third Edition for the press, in doing which I have been careful only to alter where alteration was necessary to bring the descriptive portions of the Work up to the present state of the progress of Astronomical research and discovery.

WILLIAM THYNNE LYNN.

Blackheath,
May 9th, 1882.

PREFACE TO THE FIRST EDITION.

It might with propriety be asked, what is the need of a new book on Astronomy, when so many excellent treatises already exist in the English language, of every class, both such as are familiar and rudimentary and such as exhaust the mathematical theories of the subject?

As far as the publisher of this little book is concerned, it may be sufficient to reply that a treatise was necessary to harmonise with his other "Rudimentary Treatises" on scientific subjects. The author also, when he was requested to write a work on the subject, felt convinced, after some investigation, that there did not at the time exist a book which, in small compass, and in a cheap form, would give the student a sketch of the processes pursued at present in modern observatories, together with the explanations of the leading phenomena of the science, and the most recent results of modern discovery.

There are many catechisms and treatises on Astronomy, some of which form only the introductions to other of the sciences, such as Geography, while others confine themselves to some special branch of the subject. Such treatises are generally descriptive, and confine themselves chiefly to brief

System in a cheap form was nearly ready for publication, and it is gratifying to find that the plan of that work does not interfere materially with the present Rudimentary Treatise. Mr. Hind's object, as explained in his Preface, has been to write a *descriptive* work, and "to present the reader with the latest information on all points connected with the solar system." The author's object, on the contrary, has been to write an *explanatory* work, which should at the same time contain the leading facts of the science, to serve for the purposes of illustration, and to make it acceptable to those who seek only for popular information.

It is hoped that the chapter that has been introduced on Astronomical Instruments, and their mode of use, will prove serviceable both to the general reader and to the student who is preparing to study Astronomy more systematically. The explanation also which it has been found practicable to insert concerning the theory of gravitation, and of some of the leading features of lunar and planetary perturbations, will also, it is hoped, induce the reader to seek for fuller and more philosophical knowledge in Airy's "Gravitation," to which reference has been made more than once, and which, together with the "Ipswich Lectures" by the same eminent astronomer, should be in the hands of every young student who hopes to proceed to the severer reasonings and investigations connected with the mathematical theories of Astronomy.

R. M.

GREENWICH,
March, 1852.

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RUDIMENTARY ASTRONOMY;

OR,

A CONCISE ACCOUNT OF THE PRINCIPLES OF ASTRONOMY FOR THE USE OF BEGINNERS.

INTRODUCTION.

1. The science of Astronomy has forced itself earlier upon the attention of mankind, and has been earlier cultivated, than any of the mechanical or physical sciences. This has arisen in part from the grandeur of the phenomena that are forced upon the attention of every one endued with ordinary faculties, and partly from the *necessity of attending* to the most striking of them with reference to the pursuits of daily life. Thus, the hours that can be allotted to daily labour, as well as the vicissitudes of the seasons devoted to various agricultural pursuits, day and night, seed time and harvest, summer and winter, depend upon the apparent motions of the sun, and can only be known or predicted by a study of his motions. As soon, also, as people living on the sea-coast had acquired civilisation enough to know the importance of making the ocean the means of communication between themselves and neighbouring countries, they would recognise the importance of studying the positions and the motions of those points of reference that glittered in the firmament above them, and seemed so exactly adapted to the purpose. They could quickly observe that though, at first sight, the "mazy dance" of the planets and the stars presented inextricable confusion, yet a trifling amount of observation would reduce their motions to something like order.

2. The Chaldean or the Phœnician astronomer, studying the aspect of the heavens for a whole night, would explain

to himself with tolerable precision the nature of the motions exhibited. Looking towards the north at successive hours, he would observe in one part of the heavens that the stars, if not actually at rest, yet had motions very inconsiderable compared with those in other parts, and that they appeared to turn round a point or pole, defined by a tolerably bright star, which itself appeared to be absolutely motionless. Looking towards the east he would observe stars rising successively above the horizon, or earth-bounding line, and equally proceeding in parallel directions towards the south, while in the west those that had previously occupied his attention vanished one by one, and were succeeded by others declining in the same direction. The general direction of the motion of the stars, from the east towards the west, and their apparent common motion round some one line or axis, of which a point in the heavens near the north or polar star was the termination, would be quickly recognised.

3. It would also be readily seen that the stars, though thus partaking of a common motion round a fixed axis, had no visible motion with regard to each other. Night after night the same remarkable groups would be exhibited: Orion would appear with his sword and his belt; Castor and Pollux, twins in magnitude, and conspicuous for their brightness, would preserve the same distance from each other and the neighbouring stars; Sirius would glitter with unrivalled brightness beneath them, and the general aspect of the heavens would be unchanged.

4. But there was one fact, which, as the seasons rolled onwards, they would not fail to discover, viz., that the whole of these glittering bodies had a motion with regard to the sun, that is, that either the sun moved amongst them in the course of the year from west to east through the whole circumference of the heavens, or that the stars travelled in one compact mass towards him, from east to west, in addition to their diurnal motion. Beginning their observations soon after sunset they would observe that, at the same hour of the evening (reckoned by the sun), the stars in the east were higher after a few nights, or had risen earlier, while the stars in the west were lower or nearer to setting, that is, they had all apparently been moving from east to west towards the sun, or the sun had been moving from west to east, which would be by far the simpler and likelier hypothesis. By observing, too, the stars which at different seasons rose and set very near the sun, they would be able

to trace roughly his path among them, or to map out his track in the heavens, that is, they would get a notion of the ecliptic, or the sun's annual circle. By dividing also the globe of the heavens into two equal portions by a plane drawn through the centre at right angles to the axis before mentioned, that is, by the equatorial plane, they would find that the ecliptic cut this plane in two points at the extremities of a diameter, or that the sun's motion was in a great circle of the sphere, and therefore that he moved in a plane which passes through or intersects the earth.

5. Thus far the common-sense observations of the ancient astronomer led him to a knowledge of the general diurnal and annual phenomena of the heavens. But there were other objects which would almost equally attract his attention. The moon, so necessary for the light afforded during the absence of the sun, and so interesting for the variety of the phases exhibited by her, would naturally claim a great share of attention. The track of this luminary could be very distinctly mapped out amongst the stars, and there would be no difficulty in discovering that she too moved in a great circle, that is, in a plane passing through the earth.

6. By following up these observations the ancients would, by degrees, acquire a knowledge of some of the peculiarities of the motions of this body. By tracing her motions, however rudely, they would scarcely fail to discover that the point where her orbit intersected the ecliptic or the sun's path was not stationary, but had a constant retrograde motion, and that in consequence her position in the heavens varied from year to year, and after a time they would gain a knowledge of some of the most remarkable of her inequalities.

7. Amongst the stars, too, a few conspicuous in brightness would attract their attention by an evident motion of their own. They would see them sometimes move in the order of the signs, or in the direction of the sun, and then, after appearing to rest for a period, the direction of their motion would become changed, and they would move contrary to the order of the signs; and they would not be long before they discovered that the motions of the *planetæ*,* or wandering bodies, were connected with the sun, and they would make it their business to map down these motions with the view of ascertaining the laws by which they are regulated.

* From πλαναω, to wander.

8. It is not our purpose, nor have we space, to enter at all in detail on the ancient history of astronomy, and our remarks have been made solely with the idea of pointing out to the student entering upon the science, what is the natural mode of treatment of the subject, so as to enable the mind to embrace clearly and consecutively its leading features; but before following out the plan, which has been roughly sketched, it is necessary that we first endeavour to obtain some clear notions of the means by which our own planet has been measured and rendered the basis of further operations, before we venture to apply the line and the plummet to those inaccessible bodies that by their distance present so many obstacles to our inquiries.

9. The plan, then, which we propose to pursue is, first, to explain the nature of the proofs of the ordinarily received hypotheses respecting our own globe, including its rotundity, its uniform diurnal rotation round an axis sensibly fixed and permanent, and the nature of the operations by which its actual size and figure have been ascertained.

10. We shall next devote some space to the description of the instruments, and of the mode of using them, by which the heavenly bodies are referred primarily to the centre of this our planet.

11. We shall then treat of certain corrections required to be applied to the positions thence deduced, in consequence of the disturbances produced by the sun and moon on account of the earth's spheroidal figure, and in consequence of the progressive motion of light.

12. The motions of the sun, moon, and planets will follow next in order, and we shall endeavour under this head to give some slight idea of the mutual disturbances which they experience in consequence of the law of gravitation, together with the theory of the eclipses originating in the apparent conjunctions and oppositions of the sun and moon.

13. We shall then proceed to discuss those grander features of Astronomy which are involved in the speculations and research of modern astronomers on the numbers and distances of the fixed stars, and in doing this we shall be careful to give in short compass a sketch of the vast progress which has been made during the present age.

14. In the study of any science, in however elementary a manner, some acquaintance with the rudiments of various other sciences must be presupposed. In Astronomy, an acquaintance with the chief propositions of elementary geometry

is indispensable, and the student is under great disadvantages unless he be in some degree acquainted also with plane and spherical trigonometry. We shall assume also that he has read attentively the Treatise on Mechanics in this series, and is consequently acquainted with the nature of force sufficiently to make our remarks on the mutual action of the bodies of the solar system on each other intelligible. It will be our object to divest the subject as much as possible of all unnecessary technicalities, and to explain, as clearly as our very limited space will allow, all the ordinary phenomena.

15. At the same time it must be understood, that the book is only what it pretends to be—rudimentary; and that the student who has tolerably well mastered its contents, should proceed to study the far more philosophical and complete expositions of the subject that are comprised in Airy's Ipswich Lectures,* and Sir John Herschel's Outlines of Astronomy.

* In the later Editions of this admirable work by Sir George Airy (Astronomer Royal from 1835 to 1881) its title is changed to that of "Popular Astronomy: a Series of Lectures delivered at Ipswich."—Ed.

CHAPTER I.

FIGURE AND DIMENSIONS OF THE EARTH.

16. OUR introductory chapter has shown how the most conspicuous of the phenomena of the starry heavens may be investigated and explained by an observer assisted by nothing but ordinary good faculties, who watches diligently the apparent motions of the heavenly bodies for a whole season. Such a person will be able to account for the *apparent* diurnal motion of the stars from east to west, by a *real* diurnal rotation of the earth on a fixed axis from west to east, and the apparent annual motion of all the stars in a compact mass relatively to the sun by the hypothesis of an apparent motion of the sun in the contrary direction.

17. All these phenomena will be equally well accounted for, whatever ideas we may entertain of the dimensions and the shape of the earth. But, as it is evident that the earth must ultimately be our basis for measuring everything external to itself, we will begin by inquiring by what means we derive our ideas respecting its size and figure.

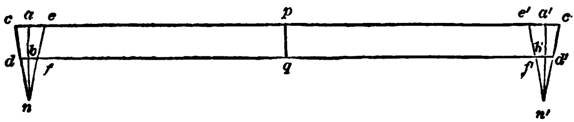
18. First, then, the earth is, roughly speaking, round or spherical, like a ball or an orange. The ordinary proofs of this fact are of the following nature:—A person standing on the sea-shore, and watching with a telescope the approach of a ship under sail, would first see the topmast and upper sails, next the mainmast and lower sails, and lastly the hull. Two ships approaching each other under sail, in like manner, first become visible to each other from their respective mastheads, the lower portions coming successively into sight. Lastly, ships have actually and repeatedly made the circuit of the globe; that is, by sailing out from a certain port in a *westerly* direction, they have returned to it in an easterly *direction, or vice versâ*. Lastly, the phenomena with regard to

the heavenly bodies, which ought to take place on such a supposition, actually do take place. Thus, to a ship sailing southwards, night after night new constellations towards the south are continually making their appearance, and those towards the north are sinking lower and lower. As the southern cross attracts the delighted attention of the mariner in one direction, his old friends the Greater and the Lesser Bear, with the pole round which they revolve, are vanishing in the other.

19. By such observations we may satisfy ourselves that the earth is, generally speaking, round, but we are still ignorant of its exact shape. And by what means are we to estimate or measure it? It would seem ridiculous to say that it is principally done by a yard measure or small standard of length, and yet it is really the fact. Small as we are with regard to the vast surface of the earth, and crawling as it were slowly on its surface, it is plain that we cannot put a girdle round it, or measure at once its whole circumference; but, in defect of that, we can measure by degrees tolerably large portions of its surface in various situations, and then by calculation find what form and what dimensions will best satisfy all the observations which have been made. But here a difficulty meets us at the outset. All bodies with which we are acquainted expand by heat and contract by cold, so that, whatever we choose for our measuring rod, it will not preserve an invariable length, and so will be very unfit to measure a distance equal to very many multiples of itself. Various plans have been devised for getting rid of this difficulty, by nicely comparing the metal bars that were to be used with some one standard bar under known circumstances of temperature, or by compensating the bars themselves by means of the application of two metals differently affected by temperature. An ingenious instance of this kind of compensation was first employed in the bars used in the measurement of the Irish Base Line,* along the east side of Lough Foyle, in the county of Londonderry, and afterwards used in India and at the Cape of Good Hope. The principle may be thus explained:—$a\ a'$ and $b\ b'$ are two bars parallel to each other; the upper one of brass, and the lower one of iron, connected by a steel piece $p\ q$; $a\ n$, $a'\ n'$, are flat steel tongues at their extremities, moving freely on conical

* See Account of Measurement of the Lough Foyle Base Line in Ireland, by Captain W. Yolland, R.N.; and Airy's Popular Astronomy, *First Lecture*.

brass pivots, allowing them to be inclined at small angles to the lines perpendicular to the bars. The lengths *a n*, *a′ n′*, are to the lengths *b n*, *b′ n′*, in the proportion of the expansion of brass to that of iron under equal increments of tem-



perature. Then the bars being made of precisely equal lengths at a temperature of 62°, the tongues will for that temperature be perpendicular to the bars, and for any other temperatures the expansions or contractions *a c*, *b d*, *a e*, *b f*, &c., of the brass and iron bars being proportioned to *a n*, *b n*, it is plain by the properties of similar triangles that the points *n* and *n′* will be invariable. The distance between those points, therefore, was used for the invariable length of the measuring bar.

20. There was still another difficulty to be surmounted. It was found by experiments that with respect to a brass cylindrical bar and an iron one, if their surfaces were equally exposed, the brass heated and cooled considerably faster than the iron bar, and it was necessary to find some means of reducing their heating and cooling powers to the same rate. This was effected by the use of another principle, viz., that the powers of radiation and absorption of heat depend upon the degree of polish of their surfaces; for, by lacquering the surface of the brass bar, and by browning and lacquering the iron one, it was found quite practicable to equalise the rates of cooling and heating.

21. Having thus obtained an invariable measure of length, it is evidently possible, by using several such bars, to measure a line of any length with perfect accuracy. But other precautions are still necessary in practice. The bars must not be placed close together lest they should disturb each other. It was necessary, therefore, to measure the small intervals between them by means of microscopes, mounted on a similar principle of compensation. Other precautions for insuring the bars being at precisely the same level and in the same straight line, it would occupy too much space to detail.

22. However, by this process, suppose we have the power of measuring a line of several miles in length with perfect

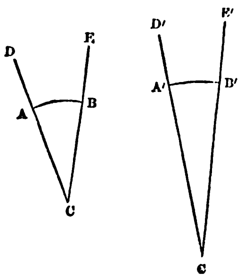
accuracy. The line must be selected with great care, over a level tract of country, as free as possible from hindrances and obstructions; and the Irish base above mentioned was admirably adapted to its purpose, running along the sand on the borders of Lough Foyle. Such a line, once measured, is the basis for a large triangulation of the country to be surveyed or measured, and the next instrument required for this purpose is a theodolite. This is an instrument for measuring horizontal angles, consisting, in its simplest state, of a pillar turning freely on a vertical axis, and carrying, on outriders, with Y supports attached, a telescope, mounted like a transit instrument, capable of being directed to any object. It has a graduated horizontal circle read by verniers carried by the vertical pillar.

23. Conspicuous objects on the summits of the hills within sight are then selected, and, by means of the theodolite, the angles which the lines joining them and the extremities of the base make with its direction are then accurately measured. Now, here a curious fact is discovered. When these angles, together with the third angle of the triangle, are accurately measured, it is always found that the sum of the three angles is greater than two right angles; and this circumstance is invariably expected, and made in some degree a test of the accuracy of the work. Now our readers, who are conversant with spherical trigonometry, know that this is always the case in all spherical triangles, the difference being known by the name of the spherical excess, and being a measure of the spherical area. This, then, is an additional proof of the earth's sphericity. Imagine, now, a network of such triangles to be measured across a country in the direction of a *meridian*, which word it is necessary to define. With regard to the heavens, it may be understood to be that great circle passing through the poles, which bisects the diurnal path of the stars from horizon to horizon, or marks their highest point or point of culmination; or, more technically, it is the great circle passing through the poles and zenith (or point immediately vertical to the observer's position). With regard to the earth, it is the intersection of this plane with the earth's surface, or the circle passing through the poles and the observer's position. Now the object of the chain of triangles, measured in the manner above described, is ultimately to obtain the length of a determinate arc of the meridian; and the direction of one of the sides *with regard to the meridian* must therefore be found, or, technically

speaking, its *azimuth* must be determined. The term azimuth also requires definition. The azimuth of an object is its direction with regard to the meridian, which we have just defined; and we shall always suppose it to be measured from the south towards the west throughout the whole circle.

24. To determine, then, the azimuth of one of the lines of the measured triangles, we must evidently know the direction of the meridian, and for this purpose the transit instrument is used. As this instrument has not yet been described, we will ask the reader to take for granted, for the present, that by its use a mark can be set up exactly in the direction of the meridian from any one of the stations of triangulation; and then, by the theodolite, the angular distance between this mark and another of the stations can be determined, which will be the required azimuth.

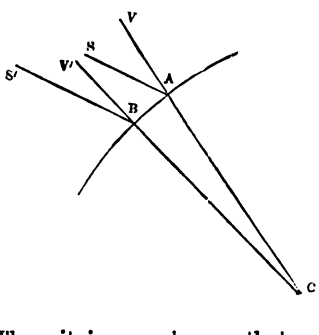
25. With these data, then,—that is, with the calculated lengths of the sides of the triangles and their azimuths,—the length of a portion of the meridian of considerable length, lying between two chosen stations, may be calculated with very minute accuracy. The line thus measured, forming part of the earth's curved surface, will be curved, and the next object is to determine the degree of curvature. To elucidate this, we will explain what is meant by different degrees of curvature. Suppose A B, A′ B′, to be two small equal arcs of different circles, whose centres are C, C′. Draw the radii, and produce them to D E, D′ E′. Then the curvatures of these arcs will be measured by the inclination of their radii at the extreme points; that is, by the angles D C E, D′ C′ E′, or, as the arcs are equal, and the angles generally are in the proportion of the arcs divided by the radii, the curvatures will be inversely proportional to the radii.



26. Now mathematicians are accustomed to consider that any curve, so that its curvature be continuous, may at any point, for a very short distance, be supposed to coincide with a circle of a certain determinate radius, called its circle of curvature, and they may use without sensible error the curvature of this circle to denote the curvature of the curve at this point. To determine, then, the curvature of any parts of the earth's surface, they endeavour to ascertain

what is the direction of the vertical line at each extremity of the arc, which they have measured as above explained, and to compare such measures at different parts of the earth's surface.

27. Now, the direction of the vertical line at any place can be determined by three separate methods: viz., in the first place by means of the plumb-line, that is, of a string suspended from a point, with a weight at the end of it; or secondly, by means of a trough of mercury, whose surface when undisturbed is always horizontal, or at right angles to the vertical; or thirdly, by means of a spirit level, that is, of a horizontal glass tube slightly curved, and nearly filled with ether, or other volatile fluid, in which case the bubble or vacant space at its upper surface always retains a horizontal direction. On one or the other of these principles, instruments called zenith sectors have been constructed, by which the zenith distances of stars in the neighbourhood of the zenith can be accurately measured. As all the instruments which we have occasion to advert to in this chapter will be more fully described in the following, we shall beg the reader to take for granted for the present, that the angular distances of stars from the zenith, or point immediately over head, can be thus measured, and he will then see very readily how this operation is rendered subservient to the finding of the figure of the earth.



28. Suppose, for instance, A and B to be two points of the earth's surface, on or nearly on the same meridian; V A C, V′ B C, verticals at the points A and B; S and S′ the apparent positions of the same star, as seen from A and B. Then it is easy to see that, as the lines S A and S′ B must be parallel to each other, the distance of the star being sensibly infinite, the difference of the angular zenith distances, V A S and V′ B S′, is equal to the angle C, formed at the point where the verticals meet each other; and this angle compared with the length of A B, previously measured, is the measure of the curvature of the earth in the neighbourhood of the points A and B, or, more accurately, for a point at the middle of A B.

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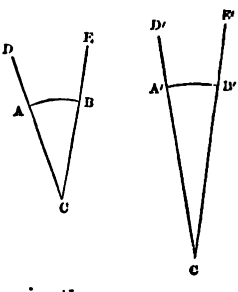

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such a figure as would be produced if a hoop were slightly flattened by pressure, and then made to revolve about the shortest diameter thus produced.

32. We can, of course, in a short popular treatise, give no intelligible account of the refined mathematical processes by which the most probable values of the flattening and of the absolute dimensions have been obtained from the measures. It is sufficient to say in this place that the measures have been most elaborately discussed by two of the most accomplished mathematicians of this century, viz. Airy and Bessel, and we will state the results at which they have separately arrived.

33. Airy's results, as given in the *Encyclopædia Metropolitana*, (article "Figure of the Earth,") are,

$$\left.\begin{array}{ll}\text{Equatorial diameter} & = 7925{\cdot}648 \\ \text{Polar diameter} & = 7899{\cdot}170\end{array}\right\} \text{miles.}$$

Bessel's results, obtained from the investigation in the *Astronomische Nachrichten*, Nos. 333 to 336, and No. 438, are,

$$\left.\begin{array}{ll}\text{Equatorial diameter} & = 7925{\cdot}604 \\ \text{Polar diameter} & = 7899{\cdot}114\end{array}\right\} \text{miles.}$$

And from both these results it follows that the polar diameter is shorter than the equatorial by about $\frac{1}{300}$ part. This quantity is technically called the *compression.*

More recently the figure of the earth has been determined with very great care by Captain A. R. Clarke, R.E., in connection with the geodetical operations of the Ordnance Survey. He finds as the most probable result that

$$\left.\begin{array}{ll}\text{The Equatorial diameter} & = 7926{\cdot}596 \\ \text{The Polar diameter} & = 7899{\cdot}706\end{array}\right\} \text{miles;}$$

The compression or ellipticity being $\frac{1}{295}$ very nearly.

CHAPTER II.

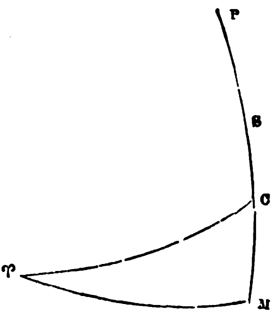
OF ASTRONOMICAL INSTRUMENTS, AND THE MODE AND OBJECT OF THEIR USE.

34. HAVING in the preceding chapters endeavoured to familiarise the student with the leading phenomena of the heavens, and with the mode of proof by which it is shown that many of these phenomena arise from the equable rotation of the earth round an axis sensibly fixed and permanent; and having finally given some idea of the operations by which the surface of our planet is measured, and its exact size and figure ascertained; we proceed, according to the plan laid down, to give a brief description of the principal instruments which are made use of in modern observatories for fixing geometrically the positions of the heavenly bodies.

35. It is assumed that the student is sufficiently acquainted with elementary geometry to know that the position of a body on a plane surface is defined by means of its distances from two fixed lines (generally at right angles to each other) in that plane; and similarly the position of a body on a spherical surface may be defined by means of its angular distances from two great circles of the sphere, at right angles to each other. One of the circles chosen by astronomers for this purpose is the equator, or the plane passing through the earth's centre at right angles to its axis of revolution, and the other is the plane passing through the earth's axis and the point where the equator intersects the ecliptic, or the plane of the sun's apparent motion. This latter point is technically called the *First Point of Aries;* and this designation was given because, in the time of the ancient astronomers, it was situated in the constellation Aries, though it has now retrograded considerably behind that constellation. *The angular distance,* then, of any heavenly body, measured

along the equator, from the first point of Aries, is called its *right ascension;* and its angular distance north or south of the equator is called its *north or south declination;* or, which is a much better mode of measuring, its angular distance from the pole is called its *polar distance.* In northern latitudes like our own, this distance is measured, of course, from the North Pole, and is called *North Polar distance.*

36. Let, for example, S be a star or other heavenly body, and let the circles ♈ C and ♈ M, as in the figure, be projections of the equator and ecliptic in the sphere of the heavens; P the North Pole, or the point where the earth's axis produced would meet the sphere; and, finally, P M, the projection of a plane passing through the axis and the body S, and therefore necessarily at right angles to the equator. Then ♈ M is the right ascension of the body; S M is its declination (in this instance north); and P S its polar distance.



37. It is the main object of astronomers to determine for all stars in the heavens, as far as is practicable, and for every planet or comet, the values of these co-ordinate arcs. In the former case, that is, for stars popularly said to be *fixed,* we shall see hereafter that their places in the heavens can, by means of certain corrections applied to their observed places, be absolutely determined with a wonderful accuracy; and with regard to the latter, their orbits can be accurately determined, and their places predicted for any time whatever.

38. We will first show how right ascensions are determined. The reader will bear in mind that the stars appear to revolve uniformly round a fixed axis in a certain space of time (called from this circumstance a sidereal day); and for the present we shall assume that they do this with perfect accuracy, and without any disturbance, either by want of absolute parallelism of the earth's axis, or by means of any motion of their own. Imagine then a clock to be set up, and regulated so that its index shall describe very nearly twenty-four hours in the time of a star's passing by the diurnal rotation from any point in the heavens till its return to it again. It is evi-

dent that, for the nearer adjustment of the clock and for the obtaining of a knowledge of its rate of going from day to day, it would be necessary to set up a fixed mark to observe this star. For instance, an observation might be made of the time of disappearance of the star, the observer looking along the side of a house whose front is nearly south, and, by watching it from night to night, and taking the time by the clock, an idea might be gained of its approximate rate of going. But if, instead of looking along the side of a house, the observer were to direct a telescope to the star, and watch the time of transit of its image over a fixed mark or wire placed in the plane of the focus of its object-glass, a much more delicate observation would be made; and the observation would be still more accurate and refined if, instead of one wire, several were inserted, and the mean of the times were taken to represent the time of passage. Now this is, in fact, what is done by the *Transit Instrument*, which we shall proceed to describe.

39. This instrument consists chiefly of an astronomical telescope, furnished with a frame of wires at the place where an image of a celestial object is formed by its object-glass, and with an eye-piece, through which the image of the object and of the wires can be distinctly viewed. It is also furnished with a cross axis, passing through its centre, and terminating in two well-turned and polished cylindrical steel pivots, whose axes are, as nearly as the artist can make them, in the same straight line, and at right angles to the optical axis of the telescope. The instrument is placed in bearings fixed to very solid stone piers, and technically called Ys, from their likeness to the letter Y. The position of the piers is so chosen, and they are so constructed, that when the ends of the pivots rest in the Ys, the axis of the pivots shall be very nearly horizontal, and that the optical axis of the telescope shall, in its revolution, very nearly sweep out the plane of the meridian, or the great circle passing through the zenith and the pole. If these conditions were all strictly fulfilled; that is, if the axis of revolution were strictly at right angles to the optical axis of the telescope, and were strictly horizontal; if the optical axis passed through the central wire of the system placed in the focus, and finally passed through any one point of the meridian; then, supposing the pivots to be perfectly cylindrical, and the tube of the telescope perfectly rigid, the *time of a body being on* the meridian would be accurately

that at which it passed the central wire. But, unfortunately, none of these conditions can ever be accurately fulfilled; and even if they were fulfilled one day, they would not be so on another, on account of the shifting or yielding of the piers, or some part of the instrument. Indeed, the great principle of modern practical Astronomy is not so much to get rid of all instrumental errors as, in the first place, to provide means for accurately measuring them, and, in the second, to allow for them when measured in the calculation of the observation. We will then proceed to show how this is managed for the instrument under consideration. It must be remembered that the conditions to be satisfied for a star to be accurately observed as it passes the meridian are three. First, the axis of revolution must be accurately at right angles to the *plane of collimation*, that is, to the vertical planes passing through the centre of the object-glass and the central wire or mean of wires. Secondly, the axis of revolution must be horizontal. Thirdly, the optical axis, which (if these conditions be fulfilled) will describe a great circle passing through the zenith, must also pass through the pole. Hence three *errors* are introduced, called respectively the *error of collimation*, the *error of level*, and the *error of azimuth*.

40. To measure the error of collimation, a distinct mark is frequently used, set up at a considerable distance from the observatory, in the direction of the meridian; but a better means is provided in the use of another telescope, set up on Ys in the northern opening of the shutters, and furnished with a wire-cross in its principal focus. By taking off the eye-piece of this latter telescope (adding a small plane reflector to illuminate the wire), and turning its object-glass towards the object-glass of the transit telescope, the wire can be seen through the eye-piece of the latter, and answers the purpose of a fixed mark at an infinite distance. Imagine, then, this mark to coincide with the central wire of the transit instrument, and imagine the eastern end of the axis to be called A, and the western end B. Then, if the instrument be taken out of its Ys, and replaced with the ends of the axis reversed,—that is, so that B be east and A west,—if the wire is still coincident with the mark, there is no error of collimation; but if they do not coincide, the distance between the two will be in angular space the double of the error to be measured. The space in question is measured by means of an apparatus called a "micro-

meter,"* with which all good transit instruments are furnished, and which we shall describe presently.

41. Let us now see how to estimate the effect of this error, or to calculate what correction is due to the time of transit of a star from this cause. Suppose the line of collimation of the instrument to deviate from the meridian a few seconds (n) towards the east; it will evidently deviate by this same space in any position of the telescope, and the error in time will be that taken by the star in describing this space by its diurnal motion. Now, stars move more slowly as they are nearer the pole, as is very evident from the fact of their describing a smaller circle in the same space of time, that is, in a sidereal day. Any of our readers who know anything of spherical trigonometry would easily make out that this slowness of the star's motion increases in the proportion of the secant of its declination or distance from the equator. Hence, since at the equator the error in time would amount to

$$\frac{24}{360} \times n^s \text{ or to } \frac{n^s}{15}; \; n^s \text{ denoting } n \text{ seconds of time;}$$

for any declination δ, the error will be

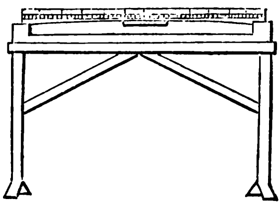
$$\frac{n^s}{15} \times \text{Sec. } \delta, \text{ or to } \frac{n^s}{15 \times \text{sin. North Polar dist.}}.$$

In strictness, there is another error which acts in the same way as that of collimation, viz. that due to the *diurnal aberration;* but this we cannot discuss now, as the subject of aberration has not yet been brought before the reader.

42. The next error is the error of level. This is measured by a spirit-level, which has been before mentioned, and which we will now describe. It consists chiefly of a hollow glass tube, nearly filled with a fluid of great mobility, such as spirit of wine or sulphuric ether, the unfilled part leaving merely a bubble occupying a considerable portion of the length of the tube. This tube is purposely curved in a slight degree, with its convexity upwards, so that, when the tube is very nearly horizontal, the bubble will rest in a definite position in the upper part. This glass tube is set in a frame of brass, and a scale is fixed to the upper part of it. It is also provided at the extremities of its frame

* *From* μικρος, small, and μετρειν, to measure.

either with hooks by which it can be attached to the pivots of the instrument, or with feet terminating in forks, by which it can be made to ride upon them. Now, suppose it is known that, when the level is attached to an instrument whose axis is horizontal, the ends of its bubble (or, more properly, its centre, which can be known from the scale readings for its two ends) occupy a certain position, then, if the axis cease to be horizontal, it is evident that the bubble will occupy a different position, known by reading its scale, and the space through which the centre of the bubble has been moved measures the inclination of the axis. The value of the scale divisions, that is, the error of level corresponding to any number of such divisions, is previously found by some such method as attaching it to a graduated instrument placed with its circle vertical, and finding how many scale divisions correspond to a known space turned through by the circle; or by placing it on a frame called a *level prover*, whose plane can be altered in horizontality by a screw, the inclination of whose thread is known. In the proper use of the level, observations are always made with it in reversed positions, that is, the scale readings are taken for the ends of the bubble, and it is then turned round and placed in the reversed position, and the scale is then read again. We cannot afford space to show how it is applied to ascertain the form and equality of size of the pivots of the instrument; but the student who may wish for farther information may consult some of the works that treat more systematically of astronomical instruments.

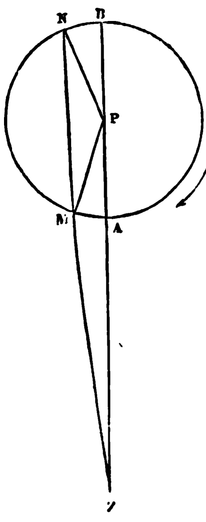


43. Imagine, now, that by this means the error of level is found to be m'', the west end of the axis being higher by that quantity; so that for any star the correction will be additive, the telescope being tilted too far east. It is plain that the angular deviation of the line of collimation axis from the meridian will become greater as the object is higher above the horizon, being nothing at the horizon and greatest at the zenith. It will, in fact, vary as the cosine of the zenith distance; and, since the star moves more slowly over this space in approaching the pole in proportion to the *reciprocal of the* sine of North Polar distance, by reasoning

in the same manner as for the error of collimation, it is plain that the correction to the time of transit will be

$$\frac{m' \times \text{cos. Zenith dist.}}{15 \text{ sin. North Polar dist.}}.$$

44. Our instrument is now, when corrections have been applied for these two errors, reduced to the same state with regard to accuracy as if its line of collimation axis always described a great circle of the heavens passing through the zenith. It will also be observed that the means are purely mechanical by which this has been effected, no reference being made to the heavens in obtaining the errors; but, since the position of the meridian is only known by its being the plane at which the stars generally culminate, or at which they come to their highest or lowest point, it is plain that, in determining the position of the optical axis of the telescope with regard to the meridian, we must have recourse to them. Now, there is a bright star near the pole (Polaris) which everybody knows—the large star, in fact, of the constellation Ursa Minor—which serves admirably for this purpose; and we will show how observations of it are made to determine the deviation of the telescope from the meridian.



45. Let A M N B represent the small circle described by the pole-star on any day round the pole; Z the zenith of the place of observation; and Z A P B a portion of the intersection of the meridian with the sphere of the heavens; Z M N, a portion of the projection of the plane swept out by the central wire of the telescope (the errors of collimation and level being allowed for or got rid of). Draw the arcs P M and P N. Then the star, proceeding in its diurnal course in the direction of the arrow-point in the figure, culminates at A, and is on the meridian below the pole at B, but it is observed by the telescope at M above the pole and at N below. Hence, in culminating, it will *pass too late by the* time taken in describing the arc A M,

and below the pole it will pass too *early* by the time taken in describing the arc B N. Now, suppose the deviation of the telescope from the meridian to be p'', then the effect of this deviation is nothing at the zenith and has its greatest value at the horizon, and, by reasoning similar to that for the error of level, it is evident that the effect on the transit of a star will be, in seconds of time,

$$\frac{p^{s} \times \text{sin. Zenith dist.}}{15 \times \text{sin. North Polar dist.}}$$

Hence, if z and z' be the zenith distances of Polaris above and below the pole, the time of describing the arcs A M and B M will be

$$p \times \frac{\text{sin. } z}{15 \text{ sin. N. P. D.}} \text{ and } p \times \frac{\text{sin. } z'}{15 \text{ sin. N. P. D.}}, \text{ or } p\ a \ \&\ p\ b,$$

where a and b are the computed values of the preceding multipliers of p. If, then, t and t' be the observed times of transit of Polaris above and below pole, the times corrected to the meridian will be $t - p\ a$ and $t' + p\ b$, and it is plain that the difference of these times is accurately twelve hours.

$$\text{Hence,} \qquad t' + p\ b - (t - p\ a) = 12^{\text{h}}.$$

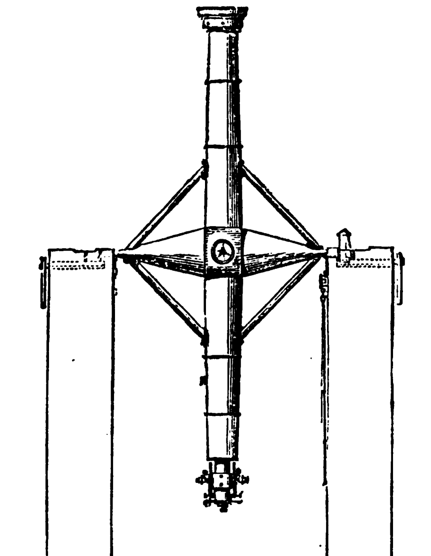
$$\text{or,} \qquad p = \frac{12^{\text{h.}} - t' + t}{a + b}.$$

46. If two consecutive transits of Polaris cannot be observed, the error can be obtained by comparing the times of transit of it and some well-known south star, passing the meridian nearly at the same time, with their tabular right ascensions given in the Nautical Almanac, each transit being affected with an error calculable as those above given; but the above method does not require the right ascension of Polaris to be known, though it requires the change of R A in twelve hours and the rate of the clock.

47. The following diagram represents a transit instrument mounted on its piers; and its use is, when it has been corrected for the errors above explained, to determine the exact time by the clock at which any celestial object passes the meridian. In its description we have, perhaps, rather passed the limits prescribed in a popular treatise; but we have thought it above all things desirable to give to persons

possessed of a small degree of mathematical knowledge an opportunity of learning, in its simplest form, the nature of this fundamentally important instrument, and the way in which it is cleared of its errors, and made to perform the work which it has to do, according to the practice of the best observatories.

48. The *clock time* at which any star passes the meridian can thus be found with perfect accuracy, and the instrument



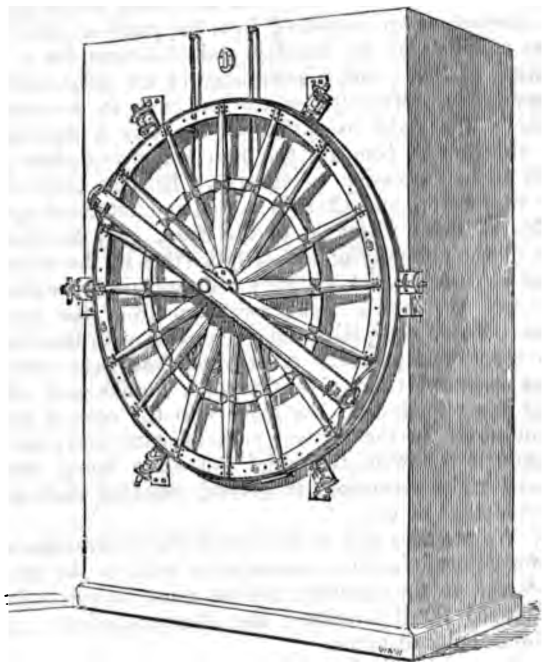
can then be used for determining the right ascension of all objects whatever, by means of their clock times of transit, in the following manner:—In the Nautical Almanac are given the places of a list of stars, nearly 200 in number, which have been constantly kept under observation for many years, in most cases during the greater part of a century. The tabular right ascensions of several of these stars observed on any night are compared with their times of transit over the

meridian, and each comparison gives what is technically called a *clock error;* these clock errors again, by comparison on different nights, give the clock rate, or its gain or loss in 24 hours; and, finally, the clock errors and rates thus found being applied to the observed times of transit of all the objects observed, their right ascensions are found, referred to the same fundamental point as that used in the formation of the "Nautical Almanac" list of stars, and therefore subject to the error of the assumed place of the equinox in that list. It has been previously mentioned that right ascensions are measured from the point of intersection of the ecliptic with the equator, and of course, for a determination of this point, a knowledge of the solar motion is indispensable. Maskelyne's method was to assume provisionally the right ascension of the star α Aquilæ, and with this star to compare the Sun and every other object which he had occasion to observe. He also observed, for some time before and after the vernal and autumnal equinox, the North Polar distances of the Sun; and, knowing the value of the obliquity of the ecliptic (that is, the inclination of the equator to the ecliptic) with sufficient accuracy, he computed the Sun's right ascension from the observed values. These right ascensions compared with the observed right ascensions gave the error which had been committed in the assumed right ascension of α Aquilæ, and afforded means for referring all the objects to the correct place of the equinox. In the present state of astronomy, the same principle is followed, the chief difference being that the assumed right ascensions of several standard stars are employed instead of one.

49. We are thus able to find one of the co-ordinates necessary for determining the position of a body in the heavens, as referred to the equator; and we must now describe the means used for determining the other co-ordinate, that is, the North Polar distance.

50. In modern English observatories this is accomplished either by a separate instrument, called the Mural Circle, or Meridian Circle, of which the telescope, which is parallel to the plane of the circle, moves in the plane of the meridian; or, still more recently, by the circle attached to an instrument called the Transit Circle, which combines the properties both of the Transit Instrument and the Mural Circle. As the mode of use of the circle in both cases is in almost all respects the same, it will be sufficient to retain here the

account of the Mural Circle which was given in the first edition of this book. This instrument, then, consists chiefly of a large circle of brass or other metal, moving in the plane of the meridian, strengthened by several stout spokes or radii, and in general shape resembling a wheel. At its centre it carries a conical axis at right angles to its plane, furnished (next to the circle) with a large steel cylindrical collar, of about six inches in diameter, intended for the

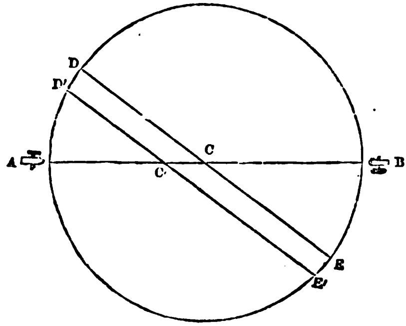


bearing of the instrument. This axis is inserted into a hollow cone, carried on a plate sunk into the east or west side of the pier built for the purpose of carrying the circle, and provided with a metal Y support for the steel bearing of the axis, and with the means for securing the circle in its proper position for use. A telescope furnished with a conical axis, which enables it to revolve freely if necessary, is *securely fastened* to the rim of the circle at opposite ex-

tremities of a diameter; and it is usual, for the purpose of getting rid of constant sources of error arising from faults in the form or graduations of the circle, to shift occasionally its position on the circle. The telescope carries a frame of several vertical wires in the principal focus (generally five), of which the middle wire is very nearly in the meridian, and is also furnished with a horizontal wire movable by a micrometer. It may be proper in this place to explain that a wire micrometer is an apparatus attached to almost all telescopes used for measuring angular space, consisting of one or more wires stretched across a frame sliding in a box, and carried in a direction at right angles to their length by means of the antagonistic action of a screw and a spiral spring. The screw carries a head, divided generally into sixty or one hundred parts, and an index is fixed beneath this head to some part of the frame or covering of the micrometer, for reading the results. When such a micrometer is attached to a telescope, the value in angular space of one revolution of the screw, that is, the angular space through which the wire is carried by turning the screw once round, may be found by measuring with it the distance between two known stars, or, if the telescope be fixed to a mural circle, by laying the wire by means of the screw of the micrometer upon a distant object, and then finding how much the circle is turned round in bringing the wire again upon the same object after the screw has been turned through a known number of revolutions.

51. Into the cylindrical rim of the circle, at right angles to its plane, is inserted a band of silver or platinum, and the accurate division of this band is the severest test of the skill and care of the artist. It is usually divided into spaces of five minutes of arc, and the whole degrees are marked round the circle, and the spaces of 15′, 30′, and 45′ carefully distinguished, to insure facility and accuracy of reading. Opposite to this divided band, and fixed firmly to the stone pier, are placed at sensibly equal distances six microscopes, furnished with wire micrometers of the construction described above, the heads being generally divided into sixty equal parts, and so adjusted that five turns of the screw carry the wire-cross very nearly from one division of the circle to another (that is, through five minutes of angular space), and therefore that one division of the micrometer-head corresponds to a second of space. The reader will observe that there are *three pairs of reading* microscopes situated at extremities of

diameters of the circle 60° apart. Now, theoretically, if the circle were of perfect form, and perfectly centered and graduated, one reading microscope would be sufficient, but, from necessary imperfections of workmanship, these conditions cannot be fulfilled, and the reading of the six microscopes will, in a great measure, get rid of any important errors arising from any one of these causes, if the instrument be moderately well constructed. We will confine ourselves to briefly explaining the effect of two opposite microscopes in getting rid of the effect of eccentricity, or false centering.



52. A and B represent opposite microscopes for reading the circle drawn in the diagram. The centre of the circle is C, but it turns round a false centre C'. Now, imagine the circle to be used for measuring the angular distance between two stars as they pass the meridian, or the difference of their polar distances (which is the primary use of the mural circle). Let A C' D' represent the angle to be measured, and draw D C E parallel to D' C' E'; then the circle, turning round C', will revolve through the angle A C' D' for the observation of the second star, and the division at D' will be under the microscope A, and the division E' under the microscope B; but, if the circle had revolved round its true centre C, the divisions at D and E would have been under the microscopes. Hence, microscope A would measure the angle in defect by the arc D D', and microscope B would measure it in excess by E E', equal to D D'. If, therefore, the means of the readings of A and B be used instead of the single readings of either, the resulting angle will be correctly measured, notwithstanding the eccentricity.

53. Mr. Pond (Astronomer Royal from 1811 to 1835) made many of his early observations by the use of two microscopes; but it is evident that by using additional pairs, distributed round the circle, much greater security is given for the general accuracy of the results, and errors of faulty *division and imperfect* form of the circle will be in a great

degree got rid of; in the ordinary use of the circle, therefore, the six microscopes are always read for every observation.

54. We have said that the mural circle measures only differences of angular space, that is, we have a reading of the circle for one object and a reading for another object, and the difference of readings is accurately the difference of their polar distances; but, if one of these objects were exactly in the pole or exactly in the zenith, the difference would be then the polar distance or zenith distance of the other object.

55. Now, theoretically, a polar point could be obtained (that is, the reading of the circle for an object at the pole) by observing a circumpolar star at its upper and lower passages across the meridian, and then, after properly correcting the results for refraction (which we mention by anticipation), taking the mean of the results; but this method would prove troublesome in practice, from the difficulty of obtaining a sufficient number of observations of the same star above and below the pole, in addition to the objection arising from the combination of observations made at an interval of time during which some change might have taken place. A much better method, and that usually practised, is to observe the angular distance between a star and its image reflected in a trough of mercury, since half the difference of the two readings gives at once the altitude, and half the sum gives the reading for an object in the horizon, whence it is easy to get the reading for an object in the zenith, or, speaking technically, the "zenith point." By observing several stars in this way, on the same evening, the zenith point can be obtained with all desirable accuracy; and hence the zenith distances for all other objects are obtained directly from the circle readings. By a skilful observer, the direct and the reflexion observations can be made perfectly well at the same transit of a star, in the following manner:—A list is prepared of the circle readings of a certain number of stars that can be conveniently or accurately observed by reflexion. A few minutes before the time of transit, the circle is turned till the telescope is in the proper direction to receive the reflected rays, and the mercury trough is also properly arranged. The observer then, after reading the six microscope micrometers, ascends the stage of the circle, and, viewing the reflected image of the star, bisects it by the wire carried by the telescope micrometer, when, by the diurnal motion, it is brought nearly to the central vertical wire. Then, running

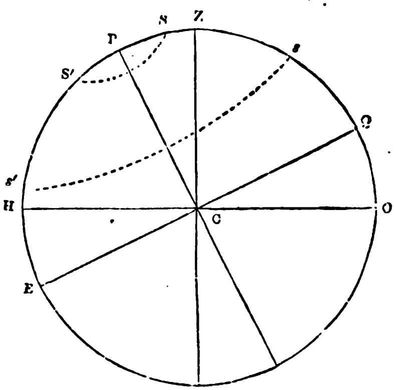
rapidly down from the stage, he unclamps the circle, and turns it till the direct rays from the star are received into the telescope, when the circle is again clamped, and the star brought upon the wire by the slow motion screw of the clamp. The six microscopes are then read again, as well as the telescope micrometer, when the observation is complete. This excellent mode of using the mural circle was first used by Airy, when Director of the Observatory of Cambridge. Another method of obtaining the value of the zenith point, now greatly practised, is by the use of what is called Bohnenberger's eye-piece; that is, of an eye-piece with three lenses, furnished with a reflector either of perforated metal or of glass for illuminating the field of view. By this eye-piece, when the telescope is placed vertically with its object-glass downwards, a distinct view is obtained of the micrometer wire, and of its image reflected from a trough of mercury placed beneath the telescope; and, by the micrometer readings corresponding to the coincidences of the two images, together with the readings of the microscope micrometers, the *nadir* point—that is, the point opposite to the zenith—is obtained.

56. Though we are rather anticipating, it is necessary to remind the student that, on account of the refraction which the rays from any heavenly body suffer in passing through our atmosphere, the readings of the barometer and thermometer are necessary for the reduction of every observation made with the mural circle, since the amount of this correction depends upon the density and temperature of the air. We shall discuss this more completely in the next chapter. However, by the foregoing explanation the reader will understand that the *apparent* zenith distance of any heavenly body can be accurately observed, and he must take for granted for the present that the *true* zenith distance can be deduced from this by application of the refraction. It then only remains for us to show how from these results of zenith distance the latitude of the place of observation can be determined, and the polar distances of the objects deduced.

57. Let E P Z Q O represent a projection of the meridian; P the pole of the heavens; Z the zenith; E Q the equator; and H O the horizon; Z C being at right angles to H O, and P C to E Q. Then it is evident that Z Q or its equal P H is the latitude of the place of observation. But P H is the altitude of the pole above the horizon. Hence we have this general

rule, *the altitude of the pole is equal to the latitude of the place of observation.*

58. Also Z P, the arc included between the zenith and the pole, is the complement of the latitude, or the *co-latitude.*



59. Now let S S′ be the small circle described by Polaris, or other circumpolar star, transiting the meridian at S and S′. Then in the course of the year a considerable number of observations of the zenith distances Z S and Z S′ may be made with the mural circle, and hence it is plain that Z P, the co-latitude of the observatory, which is half the sum of Z S and Z S′, will be determined. When this is once determined the observed meridian zenith distances can be converted into polar distances by its application, since if *s s′* be the path of any other body, P *s* = Z P + Z *s*.

60. Thus we have described how to determine the two co-ordinates which together define the apparent place of a star or other object of astronomical observation in the heavens, as referred to the celestial equator; the right ascension by a transit-instrument, and the polar distance by a mural circle. But it is evident that great advantage will be derived from combining the two instruments into one, and so determining both co-ordinates at the same observation. This has been obtained, in the improved constructions of modern times, by the Transit Circle, or, as it is sometimes called, Meridian Circle. At the Royal Observatory, Greenwich, and at other great observatories, instruments of this class have superseded the two separate instruments which were formerly used; we must therefore devote a few words to it.

60*. The Transit Circle consists mainly of a transit telescope placed in the plane of the meridian, and turning on a horizontal axis, but with the addition of two equal and symmetrical circles attached to the axis on each side of its

central cube. One of these circles is read by four or six microscopes, as in the case of the mural circle, and the other is used for setting the instrument, or for clamping it fast. From its construction, it does not admit of easy reversion for the purpose of determining the error of collimation, and this operation is effected by means of two collimating telescopes, one north and the other south of the main telescope, and with their axes as nearly as possible in the meridian, or coincident with the axis of the telescope of the transit circle. This instrument also does not admit of the easy application of the spirit-level, and the error of level is found by the use of Bohnenberger's eye-piece before mentioned, by observing the reading of the transit telescope-micrometer for the coincidence of the direct and reflected images of the central transit wire, and comparing this reading with that for the line of collimation.

61. The above instruments, viz. the transit instrument and the mural circle or transit circle, are the only meridian instruments generally used, but we must not omit here a passing mention of the altazimuth, or altitude and azimuth instrument, since an instrument of this class was erected by Airy at Greenwich in 1847, which by its solidity and firmness has produced a series of observations of the moon rivalling those made with the meridian instruments in excellence, and supplying observations for a portion of the orbit of the moon, near her conjunctions with the sun, which could be obtained by no other means.

62. This instrument consists in its simplest form of a frame revolving on a vertical axis, with which is connected a fixed horizontal circle, graduated like the mural circle. The frame carries Y bearings, for the axis of a telescope included between two vertical circles, one of which is also graduated, and the telescope revolves on its pivots like a transit instrument. Each circle is read by microscope micrometers (generally four in number, situated at equal distances round the circles), and in the principal focus of the telescope is fixed a frame carrying six vertical and six horizontal wires. Observations of azimuth and of altitude of a body are made separately in reversed positions of the vertical circles, by clamping separately the vertical and horizontal circles, taking the transit of the object as it passes obliquely through the field, over the vertical or the horizontal wires, and reading the microscopes of the horizontal or the vertical circle, accordingly as azimuth or altitude is the element observed.

For determining the deviation from verticality of the vertical axis of the instrument, and the deviation from horizontality of the horizontal axis of the vertical circle, the instrument is provided with spirit-levels attached to its revolving frame, respectively parallel to the vertical circle and the horizontal axis. We have not space, nor is it very important for our object, to describe minutely the manipulations and adjustments of this instrument, but for a minute description of that at Greenwich, we must refer to the article above mentioned.

63. Another instrument which we feel it necessary to describe is the Equatorial Instrument, which plays an important part in modern astronomy. There are some objects, such as comets and the recently discovered small planets, for which a sufficient number of observations cannot be obtained on the meridian, but which can be observed for a considerable period of time by an instrument capable of following them to other parts of the heavens, before or after their meridian passage. Such an instrument is the equatorial, which we now proceed to describe. Its general construction is similar to that of the altitude and azimuth circle, with this important difference, that its principal axis of revolution is *parallel to the earth's axis*, instead of being vertical. The pivots at the extremities of the axis have their bearings on stone piers built for them, the upper pivot resting in a Y, and the lower one working in a socket or hemispherical cup of metal. In that class of instruments most frequent in England (such as the Shuckburgh equatorial at Greenwich, made by Ramsden, to which the following description chiefly refers, as well as the large equatorial since erected at that observatory), the telescope is in the plane of the polar axis, and is carried by a strong frame-work of bars of metal connected with parallel circular plates, which carry the upper and lower pivots. This frame carries the telescope, firmly fixed between two circles (one of which, called the *declination circle*, is graduated, and the other is used for clamping) by means of a cross axis (called the *declination axis*), terminating in polished cylindrical pivots; and the telescope, together with the declination circle, is thus capable of revolving freely in planes passing through the poles, that is, in meridian planes. A graduated circle, frequently fixed to the pier, carrying the bearing of the lower part of the polar axis, serves to measure the hour angle, that is, the angle made by the meridian plane with that circle of declination on which the body is when observed, and the telescope carries a frame of fixed wires

parallel to the declination circle, and one or more wires, moved by micrometers, at right angles to them, or parallel to the equator. If the hour circle reads nearly $0^h\ 0^m\ 0^s$, when the object observed is on the meridian, then the difference between the sidereal time (that is, the clock-time corrected for the clock error obtained by comparison with the transit-clock) and the reading of the hour circle, gives the right ascension of the object observed, subject to the index error of the hour circle, which must be obtained by observations of known stars, and the errors arising from the faults of adjustment of the instrument. Hence it is evident that if a star be once in the field of view of the telescope, and the telescope be clamped, it may be kept in the field by simply turning the polar frame round the axis with a velocity equal to the earth's diurnal rotation, for the telescope itself will sweep out a conical surface, which, when produced, will meet the sphere of the heavens in the diurnal circle described by the star. The greater number of good equatorials are now provided with machinery driven by clock-work for giving this motion; and by these means any measures can be made of objects within the field of view, or any examination instituted, in the same manner as if the objects were at rest.

64. It is necessary, for the complete adjustment of the equatorial instrument, first, that its polar axis be parallel to the earth's axis of rotation—that is, that its elevation be equal to the latitude of the place (57), and that it do not deviate in azimuth to the east or west; secondly, that its declination axis be at right angles to the polar axis; and, thirdly, that the line of collimation of the telescope be at right angles to the declination axis. For the first adjustment, the Y carrying the upper pivot is fixed in a plate admitting of two motions, one in the meridian and one at right angles to it; and the amount of correction is found by observations of stars near the meridian, above and below the pole, and of other stars about six hours before they pass the meridian, and six hours after. The observations in or near the meridian determine the error of elevation of the polar axis, and the six-hour observations the error of azimuth; all the observations being made in reversed positions of the declination circle. The error of collimation is found by observing in right ascension an equatorial star in reversed positions of the instrument, that is, by taking the time of transit over the wires and reading the hour circle

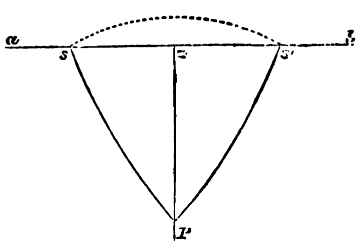
(since, for objects on the equator, the effect of a small error of position of the declination axis produces no error in the time of transit); and, finally, the joint effect of error of collimation and of position of declination axis will be found by observing, in reversed positions of the instrument, a star not very far from the pole. The carriers of the pivots of the declination axis are provided with screw-adjustments for rectification of the axis; and the error of collimation must be got rid of by shifting the position of the wire frame, by means of screw-adjustments with which it is provided.

65. The proper use of an equatorial is to observe *differentially* such objects as cannot be observed sufficiently on the meridian, by selecting some star for comparison conveniently situated, and comparing the position of the two objects; obtaining the differences of their right ascensions by their observed times of transit over the vertical wires, and their differences of polar distance by observing each object on the micrometer wire. Even when the instrument is thus used, such observations are generally inferior to those made with the meridian instruments, on account of the want of symmetry and firmness necessarily arising from its oblique position.

66. Another instrument necessary to be described is the *Zenith Sector*, or instrument for measuring small angular distances from the zenith with great accuracy. This consists of a frame revolving on a vertical axis, and carrying a telescope moving in the plane of the frame on an axis perpendicular to the plane. A graduated circular band, whose centre is the centre of motion of the telescope, is attached to the frame, and is read by a micrometer microscope moving with the telescope. For determining the inclination of the axis of rotation of the frame to the vertical, two methods may be adopted: that is, it may be done by means of a plumb-line, or of spirit-levels. The first method is that which was used in all the old zenith sectors, and in particular with the celebrated sector used by Bradley. The second method is that employed by Airy, in the sector constructed under his direction for the great English survey. Another ingenious construction, also devised by the latter, is applied to the sector actually used at Greenwich at the present time. An object-glass, with a micrometer attached to the frame that carries it, is fixed to a tube placed vertically over a trough of mercury which is distant from the object-glass by half its focal length, and is capable of rapid and easy reversion. The rays from a star

then, which tend to form an image at the actual focus of the object-glass, are reflected from the mercury, and form an image just above the object-glass; this image is viewed through an eye-piece placed properly to receive it. The star is observed in reversed positions on two wires carried by the micrometer, and the inclination of the tube is measured by a spirit-level placed in the direction of the meridian, though the instrument is so constructed that a small error of level produces scarcely any effect on the zenith distance.

66*. This chapter on instruments would not be complete without a passing mention of an important use made of the transit instrument in recent times, by placing it at right angles to its usual position, that is, with its telescope in a plane at right angles to the meridian (called the *prime vertical*), and its horizontal axis in the plane of the meridian. By observing the transits of stars not very far from the zenith as they pass the prime vertical on the east side and on the west, it is plain that we shall have data for determining the star's hour angle, and consequently, if its North Polar Distance be known, the colatitude of the place of observation. Thus, in the figure, let P and Z represent the pole and the zenith, P Z the projection of the colatitude, and *a* Z *b* that of the prime vertical; P S, or P S′, the N. P. D. of a star transiting the prime vertical at S and S′. Then the angle S P S′ (expressed in time) will be the difference of the observed times of transit, and the half of this difference will be the hour angle, or angle S P Z, which is therefore known; and, the North Polar Distance of the star, or S P, being also known, we can readily find Z P, or the colatitude, by solution of the spherical triangle S P Z. The above is only a very imperfect sketch of this method of finding the colatitude of an observatory, which needs much refinement in carrying it out, when great accuracy is required. It is absolutely the best existing method, and many modern observatories are furnished for this purpose with a transit instrument in the prime vertical.



CHAPTER III.

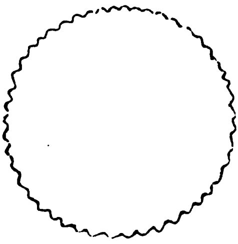
ON REFRACTION, PARALLAX, ABERRATION, PRECESSION, AND NUTATION.

67. If every object in the heavens were really in the position in which it appears to be, and if the points of reference were also fixed and permanent, the business of the astronomer would be comparatively easy; but the fact is the very reverse of this.

68. The objects themselves will appear differently situated to observers on different parts of the earth's surface from two distinct causes, the one being that the rays by which they are seen are bent out of a straight line in their passage through the different strata of the atmosphere, and the other being the spheroidal figure of the earth. The first effect is common to all the heavenly bodies, and is called refraction; the second affects sensibly the positions only of those bodies whose distances are not immeasurably greater than the diameter of the earth, such as the Sun, Moon, Planets, and Comets. The fixed stars are all placed at distances so vast, that the displacement from this cause is absolutely insensible; and even that produced by the motion of the earth in its orbit, which produces for measurement a base of not much less than two hundred millions of miles, is also insensible, except in a very few instances, which we shall speak of hereafter.

69. Again, the two points of reference for determining the positions of the heavenly bodies, viz. the pole and the intersection of the ecliptic and the equator, are not fixed. The pole of the heavens, besides having a slow motion, by which it is carried always in the same direction, so as to describe round the pole of the ecliptic a small circle in the sphere *in about* 25,868 years, is also disturbed irregularly

by the action of the sun and moon on the spheroidal earth: so that it does not describe this path quite uniformly, or in an exact circle, but traces out in the heavens a kind of zigzag line, similar to that given in the figure, and by this means gives occasion for troublesome corrections to be applied to the places of every object observed.



70. Lastly, there is a displacement of all the heavenly bodies, arising from a cause totally different from the former, that is, from the velocity of light combined with the orbital motion of the earth. This displacement was first detected by the illustrious Bradley, by means of a long and excellent series of observed zenith distances of γ Draconis, a star of nearly the third magnitude, passing the meridian of Greenwich within 2′ of zenith distance, so that the refraction is quite insensible, and the observations are free from the uncertainties which it produces in all those of which the zenith distances are considerable.

71. Now, before an observation can be rendered available for the ulterior objects of astronomical science, it is necessary that it be corrected for all the causes of displacement which have been mentioned; and therefore, in this stage of our work, it will be necessary to give such explanations of them all, and of the methods of computation by which they are allowed for, as our plan will admit of.

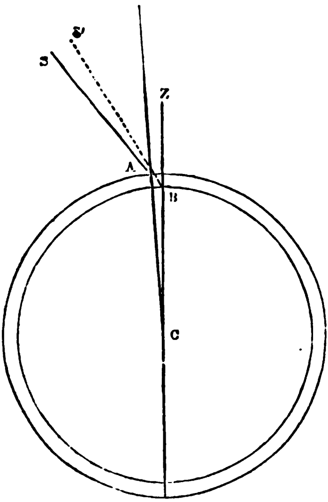
We commence with REFRACTION.

72. Our readers, we will presume, are in some degree acquainted with the science of optics, or at least they are so far acquainted with it as to be aware that a ray of light, in proceeding out of a rarer into a denser medium,—from air into water, for example,—is bent out of its course in such a way as to make a smaller angle with the perpendicular to the surface separating the two media. The familiar experiment of partially immersing a straight stick in a basin of water will be immediately suggested to the memory of our younger readers: the stick no longer appears straight, but broken at the surface of the water, so that the part below the water appears higher than it really is. The law of optical refraction is this, that for the same media the sine of the angle of incidence is always proportional to the sine of *the angle of refraction.*

73. Now, the earth is enveloped by an atmosphere extending several miles in height, and of sufficient density to bend out of their course the rays of light proceeding from the stars and planets, which are incident obliquely on its surface. At the zenith the rays fall perpendicularly on the surface, and suffer no refraction; but for every other direction they are bent or refracted, and the more so as they come from a point further from the zenith or nearer to the horizon. Any uncertainty in the amount of this refraction will vitiate an observation of any heavenly body to that amount; and therefore great pains have been taken by various eminent astronomers, not only to discôver the laws by which the refraction is regulated, but, by observations made for the purpose, to discover its exact quantity, and, finally, by means of tables, to render the amount in every given case easily calculable. We will proceed, then, to show the nature of the hypotheses on which the formulæ for the construction of these tables are based.

74. If the atmosphere were of uniform density, and if the density were always the same at the same place, the law of sines given above for optical refraction would be immediately applicable; and there would be no difficulty in devising a formula to represent numerically the exact value of the refraction in every case. But the density is, in the first place, not uniform; the strata nearest the earth being heaviest, and those at the boundary of the atmosphere of extreme tenuity. Again, the density varies according to the temperature, and according to the height of the mercury in the barometer; and the refraction will therefore depend upon these elements, as well as upon the zenith distance. It is usual, then, to calculate what the refraction will be for some standard readings of the barometer and thermometer; and then, by means of the known laws of aëriform fluids, to calculate how it will be altered, or by what factors it must be multiplied to represent the actual refraction at the time of observation. The standard height of the barometer chosen in English tables is 29·6 in., and the standard temperature 50° of Fahrenheit's scale; and for any other higher or lower values, the refraction will vary according to the direct proportion of the actual height of the barometer compared with the standard height, diminished or increased in the proportion by which the mercury in the barometer, and the volume of the air, have been increased or diminished by higher or *lower temperature.*

75. Imagine now a ray of light to proceed from an object whose zenith distance is z; that is, to be incident obliquely on the outer surface of the atmosphere, as is represented in the figure, wherein the inner circle represents the surface of the earth, and the outer circle the boundary of the atmosphere; Z is the zenith, and S A B the path of a ray coming straight from S to A, but bent into a continuous curve between A and B, till it reaches the eye of a spectator at B. The direction in which the object will be seen is determined by drawing the tangent B S′ to the curve at B; and, as the convexity of the curve is turned towards the vertical, it is plain that the apparent place of the object will be above its true place, or the zenith distance is diminished by refraction.



Now, if the height of the atmosphere were not very small compared with the earth's radius, it would be an extremely difficult problem to determine the whole amount of refraction which the ray has undergone, but as the height is certainly not much above $\frac{1}{100}$th part of the radius of the earth, and the *effective* height, as causing refraction, is much less than this, the supposition of a uniform density is almost sufficiently exact; and, indeed, the general solution of the problem is in practice subjected to such approximate assumptions, that the result is nearly identical. The result of the investigation is, that for small zenith distances, the refraction varies as the tangent of the zenith distance; and that, for the larger zenith distances, the refraction thus computed requires a correction varying as the cube of the tangent of zenith distance. In very great zenith distances still nearer approximations are necessary; and below 85° the amount becomes extremely precarious, on account of the unequally heated portions of the earth's surface that the ray meets with in its passage.

76. *For obtaining by* observation the actual values of the

numbers entering into the formula for refraction, circumpolar stars are very usefully employed. γ Draconis, for instance, passes the meridian very near the meridian of Greenwich, and its refraction is scarcely sensible. If, then, the latitude of the Observatory be known, an observation of the mural circle above the pole, compared with one below the pole, will give the whole amount of the refraction for a zenith distance of about 76°; and this observed value equated to the value given in the general formula, will give the value of the constant quantity that enters into it. Bradley employed the greatest and least zenith distances of the sun (that is, the zenith distances at the summer and winter solstices) for obtaining data for the computation of his table of refractions. The best modern tables of refraction are those given by Bessel in the *Tabulæ Regiomontanæ*, and they are exhibited in a much easier form for use in the Appendix to the Greenwich Observations for 1836.

77. In connection with refraction, we may take the opportunity to make mention of the ordinary phenomenon of twilight. The sun is actually visible to us some minutes after he has really sunk beneath the horizon, by means of the refraction of the rays by which he is seen. But, after he has so far descended beneath the horizon that no rays directly reach us, a portion of his light still reaches us in a secondary way, after being reflected from the vapours of the different strata of the atmosphere, and from the minute solid particles of whatever kind which float within it. This reflexion, by which light is brought to us as the sun descends, takes place from still higher strata; the light therefore gets more feeble, and finally ceases, or gives place to total darkness, when the sun is about 18° below the horizon.

78. The apparent zenith distances, then, which have been observed with the mural circle, are corrected by the addition of the refractions, computed from tables, constructed on the principles above exhibited, and are thus converted into *true zenith distances*; that is, to zenith distances as observed at the surface of the earth. The reader must, however, bear in mind that though the astronomer has thus availed himself of all the resources of science to get rid of the vexatious effects of the atmosphere in disturbing the places of the heavenly bodies, yet, for objects at a considerable zenith distance, an uncertainty yet remains, dependent chiefly on the varying state of local weather and climate, sufficient t

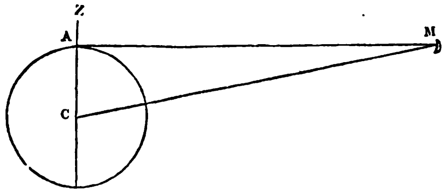
prevent the attainment of very minute accuracy in single observations, or even in the means or averages of several observations of the same object. We shall see better the importance of this remark when we come to the more refined speculations of modern astronomy, respecting the distances of the fixed stars and other cosmical problems.

79. In the ordinary processes of astronomy, however, we may assume that the stars are at such distances as, if not actually infinite, are incapable of measurement. We may also assume, without the risk of the smallest conceivable error, that rays drawn from any one of them to the centre and to any point of the earth's surface are absolutely coincident; that is, we may assume that the observations have been made at the earth's centre, and referred to a plane parallel to the plane of the sensible horizon of the observer's position. By application, then, of the colatitude, the place of the star is correctly referred to the *true pole*, or the *apparent polar distance* is correctly derived, at whatever part of the earth's surface the observation was made.

80. But, for objects whose distances are finite and measurable, such as the sun, moon, and planets, this is not the case: the polar distances then depend upon the observer's position, and, before they can be compared, they must be referred to some common point, which will, of course, be the centre of the earth. The nearer the object is, the greater will be the angle between lines drawn from it and the two points of observation on the earth's surface, or the greater the *parallactic* displacement. The consideration of *parallax* follows, therefore, naturally after that of *refraction*, and the laws by which it is calculated for the sun, moon, and planets must be now investigated. It is evident that the most conspicuous effects of parallax will be exhibited in the moon, our nearest neighbour; and this planet will therefore first claim our notice. Her average distance we shall find in the sequel to be about 60 radii of the earth, or, in rough numbers, nearly 240,000 miles. It is evident, therefore, that when she is in our horizon, the angle made by two lines drawn from her centre, one to the earth's centre, and the other to our position on the surface, will have for its tangent $\frac{1}{60}$, or the *parallactic angle*, or *horizontal parallax*, as it is called, will be rather less than one degree.

81. Thus, if A be an observer's position, C the centre of the earth, and M the moon, the angle A M C is the horizontal *parallax*; and a certain portion of this, easily calculable, and

amounting generally to a quantity varying from 30′ to 50′, according to the zenith distance, is the correction to be applied to deduce the observation from the surface to the centre of the earth; that is, to deduce the *Geocentric Zenith Distance* from the *True Zenith Distance.*

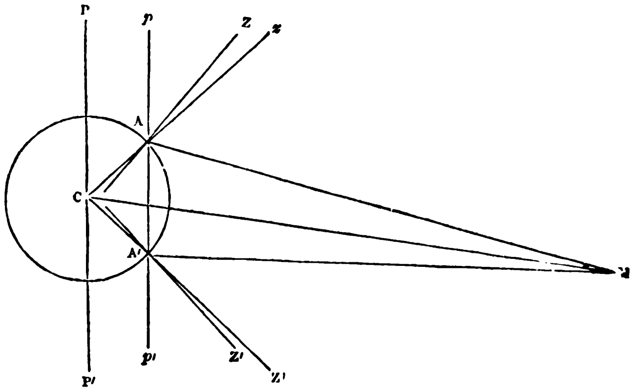


82. We will now see how the amount of the lunar parallax is detected and measured. In the first place, it is evident that the farther separated two stations are with regard to latitude, the greater will be the apparent displacement of the moon's place with regard to the pole, or the greater the observed differences of polar distances. If, then, we have observations made in two observatories, the one situated in a high northern, and the other in a low southern latitude, those observations will be suitable for the purpose of measuring the parallax. It is also desirable that the observatories be situated nearly on the same meridian, since the moon, being a very quickly moving body, will have changed her polar distance considerably in passing from one meridian to another widely separated; and the reduction necessary on account of her orbital motion will not only be troublesome, but will be precarious also on account of the refined knowledge of her motions which it will presuppose.

83. Now such observatories exist, the one at Greenwich, in north latitude 51° 28′ 38″, and the other at the Cape of Good Hope, in south latitude 33° 56′, and east longitude $1^h\ 13^m\ 55^s$. The change of moon's polar distance during the time of her passage from the meridian of the Cape to that of Greenwich, forming so small a part of her whole daily motion in polar distance, can be calculated with sufficient accuracy from very approximate elements of her orbit corrected by her observed daily motion; and we may consider the comparative observations to be made at the same moment of absolute time on the same meridian—that of Greenwich, for example.

84. We will now proceed to show how such observations determine the amount of lunar parallax, and consequently the moon's distance on which it depends.

Let, then, A and A′ be two stations on the same meridian of the earth supposed to be spheroidal, whose centre is C; M the moon. Draw the verticals A Z and A′ Z′ to the surfaces at A and A′, and A p, A′ p', parallel to the polar axis, P C P′. Join C A, C A′, and produce them to z and z'. Draw also A M, C M, and A′ M. Then the ellipticity of the spheroidal earth being known (see Chapter II.), the angles Z A z, and



z' A′ z', called the angles of the vertical, which the verticals make with the lines joining the points of observation with the earth's centre, can be computed by the ordinary principles of the conic sections, and these being subtracted from the observed zenith distances Z A M, and Z′ A′ M, the angles z A M and z' A′ M become known; or, since z A M = A C M + A M C, and z' A′ M = A′ C M + A′ M C, the sum of A M A′ and A C A′ becomes known. But A C A′ is known from our knowledge of the earth's shape, and of the latitudes of the two stations. Hence we have the parallactic angle at M, or the sum of the parallaxes observed at A and A′. To deduce from this an expression for the lunar parallax, which shall be generally useful in correcting the individual observations, a little more consideration of the law which it follows will be necessary. Confining our attention to the Greenwich station, the parallax is represented by the angle A M C. Now the sine of z A M (= angular distance from Geocentric Zenith) : sine of A M C : : Moon's distance, C M : earth's *radius at Greenwich.*

Hence,

$$\text{sin. } AMC = \frac{\text{sin. } zAM \times \text{Earth's rad. at Greenwich}}{\text{Moon's distance}}.$$

Now if at the same time another observation were made at the equator when the moon was on the horizon, we should then have

$$\text{sin. of horizontal equatorial parallax} = \frac{\text{Earth's equat}^{l}\text{. radius}}{\text{Moon's distance}}.$$

Hence, by division,

$$\frac{\text{sin. } AMC}{\text{sin. hor. eq. par.}} = \frac{\text{Earth's rad. at Greenwich}}{\text{Earth's equatorial rad.}} \times \text{sin. } zAM.$$

Call then horizontal equatorial parallax $= P$, and

$$\frac{\text{Earth's radius at Greenwich}}{\text{Earth's equatorial radius}} = r, \text{ a known quantity.}$$

Then, $\quad$ sin. parallax $= r$ sin. P $\times$ sin. z A M.

Let, now, p and p' be the parallaxes, which together make up the whole angle A M A$'$; and z and z' the corresponding reduced zenith distances; then,

sin. $p = r$ sin. P $\times$ sin. z, and

sin. $p' = r'$ sin. P $\times$ sin. z' (r' being analogous to r, for the station at the Cape); also $p + p' =$ A M A$'$ is a known quantity.

From the above equations the moon's horizontal parallax for the distance C M can be calculated. Hence the distance C M itself can be calculated in terms of the earth's radius, and the shape of the orbit of the moon being supposed known, we can obtain her mean distance.

85. For the sake of such of our readers as are not conversant with mathematical symbols, we may observe that, in the quadrilateral figure, M A C A$'$, the sides A C and A$'$ C, as well as the angles at A, C, and A$'$, are known; and hence it is plain, by simple geometrical considerations, that the sides A M, C M, and A$'$ M can be found. Thus, if A A$'$ be joined, the angles C A A$'$ and C A$'$ A, as well as the chord A A$'$, can be computed. Hence the angles M A A$'$ and M A$'$ A, as well as the side A A$'$ in the triangle A M A$'$, are known, and the sides A M and A$'$ M can be computed. Finally, C M can be computed, or the moon's distance from the centre of the earth.

86. Our *readers* will now better appreciate the importance

of those geodetical operations described in the preceding chapter, by which the earth's size and form have been accurately obtained in terms of an invariable measure of length. The base which has been used in this first instance of the extension of the measure to the heavenly bodies is, in fact, the chord A A′, with the angles at its extremities. The base is small compared with the distance to be measured, and the triangle is not what would be called in geodesy a *well-conditioned triangle.* Still it is the best the circumstances admit of, and far better than we can get for the sun and planets, which are at immensely greater distances from us than the moon, and for which, therefore, the base for measurement is comparatively very much smaller.

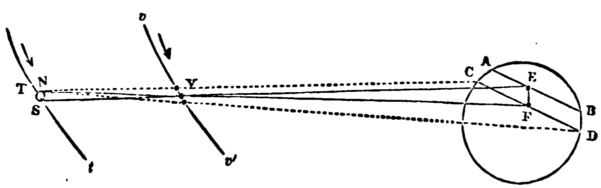
87. Even for the moon a slight inspection of the preceding figure will show that very small errors in the angles M A A′, M A′ A, and therefore in the observed zenith distances, will entail a large error in the distance C M; but if, as in the case of the sun, the base A A′ were, compared with the distance to be measured by means of the angles at its extremities, only $\frac{1}{400}$th part, it is plain that the unavoidable errors of observation and calculated refraction would bear so large a proportion to the angle A M A′, that the result would be unattainable by this method. Now this is precisely the case with regard to the sun, whose horizontal parallax is less than 9″, and his mean distance from the earth about 92,400,000 miles.

88. Other methods must therefore be employed in this case; and it fortunately happens that there are two methods of observation, one of which can be frequently applied, and the other but very rarely, which have enabled astronomers to get a very close approximation to the value of the solar parallax. The applicability of both these methods depends upon the fact, that there is a law connecting the distances of the planets from the sun with their times of revolution round that body, which enables us, after having found correctly the parallax of any one of them, to infer all the rest. This law we shall enunciate further on; but at present it is sufficient to say that advantage has been taken of it to make the observations of the next inferior and next superior planet to the earth, viz. Venus and Mars, subservient to the finding of the solar parallax.

89. Venus revolves in an orbit smaller than the earth, and sometimes, though very rarely, crosses the plane of the earth's *orbit in a direct line* between it and the sun, so as to appear

like a black spot on his surface. Such "transits of Venus," as they are called, occurred in 1761 and 1769; the last took place in 1874, and the next will occur on the 6th of December in the present year (1882). James Gregory was the first geometer who perceived the importance of the observations of the "transits" in relation to the solar parallax; but great credit is due to the illustrious Halley for the special attention he called to them. For observing the transit of 1761, the British Government sent out Dr. Maskelyne to St. Helena, and Mr. Mason to the Cape of Good Hope, to make observations to correspond wth those which would be made in Europe, in many parts of which continent it would be visible. The only northern country in which the transit of 1769 could be observed was part of Lapland; and after such deliberation as to the chocie of a southern station, it was determined by the British Government to send out an expedition to the islands of the South Pacific Ocean, under Captain Cook. This celebrated navigator chose Otaheite (Tahiti) for his station, and there the observations were made successfully.

90. The observations made at the two transits have been very fully discussed, but we have not space to enter into the etails of the discussions. Our object at present will be merely to give a brief sketch of the principles of the methods employed in deducing the parallax of the sun from the observations.



In the above figure, suppose A C D B to represent the disc of the sun at a time near the middle of the transit; V the place of Venus, and T that of the earth. Draw lines through N and S, the northern and southern stations on the earth, through V, till they meet the sun's disc at E and F. Then the planet will appear to the observers at N and S like a black spot on the sun, at the points F and E respectively;

and the more widely separated the stations are with regard to geographical latitude, the larger will be the interval E and F, and the greater the difference of the chords A B, C D, described by the planet in its transit across the disc. As the student has not yet been introduced to a knowledge of the motions of the planets, nothing but a bare outline of the problem can be rendered intelligible; but enough can be shown to exhibit the principle of the method. The earth and Venus both revolve in the same direction round the sun in planes inclined to each other at a small angle, the velocity of Venus being greater than that of the earth. The times of revolution of the planets are also connected with their mean distances by a very simple law, so that the times being obtained by observation, the proportions of their distances can be inferred. At the time of a transit of Venus, the planet must either, in descending beneath the ecliptic, or in ascending above it, meet it in a point which is in a direct line with the earth and the sun; that is, technically speaking, it must be in its *node* when in conjunction with the sun; and this is the condition for determining whether a transit will take place. Let the earth be moving in the direction T t, and the planet in the direction v V v', and suppose, for simplicity, that the plane passing through the two observing stations, N and S, and the earth's centre, is perpendicular to the ecliptic, and that the rotation of the earth is neglected; and suppose, finally, that the earth being absolutely at rest, Venus moves in the direction V v' with the excess of her velocity over that of the earth, which, in fact, represents her relative motion properly. Then, to a spectator at N, Venus will appear to enter upon the sun's disc at C, and, traversing it in the sensibly straight line C D, to go off at D. Similarly to the observer at S, the planet will appear to describe the more northerly line A B, entering at A, and going off at B. The principal observations at each station will consist in taking accurately the times at which the ingress and egress of the planet take place. On entering upon the disc a small, but very perceptible, notch will be made instantaneously on the limb, which can be observed with very great accuracy. Then when the planet is completely on the disc, the time of separation of the limb can also be observed, but not with so great accuracy: however, the mean of these times, corrected for curvature of limb, will represent very well the time of ingress of the centre, and similarly the time of egress will be observed.

Hence the time taken by the planet in describing the chords A B and C D will be known. The velocity, too, of Venus is sufficiently well known from the tables of her motion; hence the angular measures of A B, C D, will be known, and consequently the versed sines of the chords can be calculated. Thence, finally, we have the measure of E F, as seen from the earth. Now the mean distance of Venus from the sun is to that of the earth nearly as 72 to 100; and therefore the distances of Venus from the sun and earth respectively are as 72 to 28 nearly, or as $2\frac{1}{2}$ to 1. Consequently, E F, measured on the disc of the sun, is about $2\frac{1}{2}$ times the arc which the earth's diameter would subtend there at the distance of the earth, or five times the arc which would be subtended by the earth's radius; that is, five times the sun's horizontal parallax. Any errors, then, which are made in the observations will, as affecting E F, be divided by five, and hence the accuracy of the method is apparent. We have in effect the sun's parallax represented to us on a greatly exaggerated scale, and can take advantage of it to measure this important element of our system with an accuracy attainable by no other method. It will not be difficult to show what will be the effect, on account of the earth's rotation, of choosing situations differing considerably in longitude; but it is rather too complicated for elementary illustration.

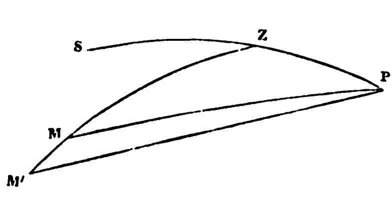
91. Besides the British expedition fitted out for observing the transit of 1769, others were equipped by the French, Russian, and other Governments, and great pains were taken in choosing such stations as would produce the best data for the solution of the problem. On the whole, the observations were considered to be very satisfactory, and the resulting horizontal parallax of the sun, as deduced by Encke, was $8''\cdot571$, a result which more recent investigations have proved to be too small. It may be mentioned, however, that Mr. Stone* has more recently rediscussed the original observations and obtained the result $8''\cdot91$, agreeing very closely with those derived from the parallax of Mars and from the observed velocity of light.

92. The last method which we shall mention for finding the solar parallax is by observations of the planet Mars; and, indeed, with the exception of that above described, it is the only method which can give results of moderate accuracy.

* Now Radcliffe Observer at Oxford.

Mars is the nearest planet describing an orbit exterior to the earth, and at certain times approaches so near that his distance from the earth is only one-third of that of the sun, or so that his horizontal parallax is about 27″. Now, this is a quantity which can be measured, by comparative observations made at Greenwich and the Cape of Good Hope, with considerable accuracy, by means of methods which get rid of that pernicious influence exercised by refraction on all delicate comparisons of polar distances absolutely measured. Suppose, for instance, the polar distance of Mars be compared, both at Greenwich and the Cape, with that of a neighbouring star, by means of the micrometer attached to a mural circle or an equatorial. The absolute polar distance of the star as observed at both places is the same, so that the differences of the measures give immediately the effect of parallax; and these are either altogether independent of refraction, or the effect is calculable without sensible error. The remaining errors are chiefly those of observation, and, these being purely casual, can be got rid of by sufficiently increasing their number. The only objection to the method is, that the stars lying in the path of Mars are generally so small and faint, that they are observed with difficulty by the ordinary meridian telescopes; but the great transit circles have now done away with the objection as regards the Observatories of Greenwich and the Cape of Good Hope.

93. There is still one way in which the parallax can be deduced by means of extra-meridional observations of Mars made at one and the same station. Let P Z S be a portion of the meridian, Z the zenith, P the pole, and M the position of the planet Mars, east of the meridian as seen from the



earth's centre, but depressed as viewed from the station whose zenith is Z in the vertical circle Z M to M′. Then the *parallax in time* by which the planet would come too late upon the wires of an equatorial instrument is measured by the angle M P M′, and by this quantity would its observed right ascension be too great. Similarly, if observed west of the meridian, the observed right ascension would be too *small by a similar* quantity. If Mars, then, be compared

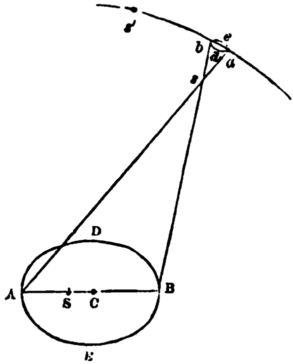
with a star lying in the same parallel of declination (by taking the clock-times of transit of both objects over all the wires) several hours before passing the meridian, and again several hours after, these right ascensions, when reduced by the known motion of the planet to the same time, will differ by a quantity depending on the parallax, and from which it can be calculated. Generally the observations cannot be made with sufficient accuracy to get results available in the present state of astronomy, even if we omit to mention the difficulty of obtaining the requisite observations at sufficient distances on both sides of the meridian. A series of observations of this kind was, however, made at Greenwich at the opposition of Mars in 1862 with considerable success.

94. Before leaving the subject, we will briefly mention a parallax in its connection with the fixed stars. We have before said (79) that the distance of the nearest of the stars is so great that it would be absolutely hopeless to endeavour to detect any displacement by observations at different points of the earth's surface; but this might not be the case with observations made at opposite points of the earth's orbit, which presents a base for measurement of about 184,800,000 miles. Surely we might imagine that, however vast the distances of the stars, unless they were actually infinite, we should be able to detect in them some difference of position by observing them at intervals of six months, during which time the earth has shifted its position by this enormous quantity.

95. And so reasoned Flamsteed, and several succeeding astronomers, in the infancy of accurate theory and accurate observing. Before the discovery of the aberration of light and the nutation of the earth's axis by Bradley, all their efforts were directed to the discovery of annual parallax, and the stars seemed to be removed to greater distances precisely in the proportion in which observations were rendered more accurate by improvements in instruments and the use of them, and as the causes of the displacements, at first presumed to be due to parallax, were accurately known. At length Bradley announced, as the result of his own at that time incomparable observations, that if a parallax of any star existed to the amount of one second, he should discover it; and since that time the ingenuity of astronomers has been employed in inventing methods for the estimation of quantities much less than this, by observations and instruments *especially* devoted to the purpose. We will see,

in the first place, what is the nature of the displacement to be measured.

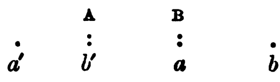
96. Let A D B E be the orbit described by the earth round the sun, S, in the course of a year; A B, two opposite points of the orbit; *s*, a star *not* at an infinite distance (that is, at a distance that may be discoverable by observation). Draw A *s*, B *s*, and produce them. Imagine also the cone which would be swept out by one of these lines during the progress of the earth in its annual circle; then it is evident that the star itself will appear to describe the small orbit,



a d b e. Now, these points, *a d b e*, lie sensibly in a plane, cutting an oblique cone in a section not parallel to its base, and will therefore be an ellipse described about its mean place. Suppose, now, we had another star, *s'*, at an immeasurably greater distance than *s*, and situated, for example, in the arc *a b* produced; it is plain, by looking at the figure, that its angular distance from *s* would appear to an observer on the earth's surface to vary, being least at *b*, greatest at *a*, and having its mean value at *d* and *e*. If, then, we had an instrument by which we could measure *very accurately* the distances of the stars *s* and *s'* in angular measure, the variations, when observed, would give us means of determining the size of the apparent orbit described by *s* round its mean place, and from this we could determine the parallax of the star, and consequently its distance from us.

97. Now this is precisely what was done a few years since by the celebrated astronomer, Bessel, with regard to a remarkable star in the constellation Cygnus (61 Cygni), by means of an equatorially-mounted telescope, called a *heliometer*. A heliometer (so called from the facility with which the sun's diameter and other large arcs can be measured with it) consists, in fact, of a telescope with its object-glass divided into two equal parts by a section through its centre. These parts are placed in contiguity in the tube of the telescope, *so as to lie in the* same plane, like an undivided glass, and,

by means of an apparatus of rods and screws, acted on from the eye-end of the telescope, are made to slide past each other, and a scale is provided which measures the degree of the separation of their centres. By this means, each half object-glass produces separate images of the objects observed, and the angular space by which they are separated will be proportional to the distance of the two centres of the half object-glasses. There is also an apparatus provided, by means of which the object-glass can be turned round in the tube, so that the direction of the two images (which is always parallel to the common section of the glasses) can be put into required positions. If, then, they be put into the direction of the diurnal motion of the star, the times of transits of its images, over a wire at right angles to their direction, will, when properly reduced, give their angular distances in terms of the scale divisions; and, the value of the divisions of the scale being thus known, the instrument may be used to measure the angular distances of stars or other objects not far apart. Thus, let A B be two stars, and suppose the screw, acting upon the segments of the object-glass, to be turned, and the object-glass itself to be turned round in the tube, till the separate images occupy the positions A, B; *a*, *b* (*a* being at a very small distance immediately below B); then it is evident that the object-glasses have been separated by a quantity representing the angular distance of A and B. In like manner, the images *a* and *b* can be brought into similar positions, *a′*, *b′*, on the other side of A, B. It is evident, then, that for these different positions of the images, the difference of scale readings corresponds to the double of the distance of A, B; and this can be reduced to arc by the known value of the scale.



98. Now the star 61 Cygni is double, consisting of two stars of nearly equal magnitude (the 6th), at a distance of a few seconds from each other. The star forms what is called a binary system; that is, it is proved, by observations continued since the year 1781, that the two components revolve round each other, being connected by gravity, or by some similar tie, like our sun and planets. They also move together through space, with a large proper motion amounting to several seconds per year. From these circumstances, all astronomers have been led to look upon this star *as probably near* enough to us to enable us to detect its

distance by observation; but it was not till Bessel made his celebrated observations with the heliometer, at Konigsberg, that any satisfactory result could be obtained. He found two stars very minute, but perfectly observable, each at a distance of several minutes from 61 Cygni, the one lying nearly at right angles to, and the other nearly in the direction of, the line joining the components, and he made a long series of measures of their distances from the middle point between the components. These measures, when properly treated, exhibit a series of fluctuations agreeing with those which would arise from annual parallax, and leaving no doubt of its existence in the minds of persons familiar with the subject. The result is, that the annual parallax, that is, the angle which the radius of the earth's orbit subtends at the distance of the star, is rather more than three-tenths of a second of space, corresponding to the enormous distance of 600,000 radii of the earth's orbit; or, to a quantity greater than 600,000 times 92,400,000 miles.

99. This star, then, probably one of the nearest, is placed so far out of the range of the solar system, that even using our distance from the sun as the unit of measure, imagination almost fails us in conceiving the enormous interval that separates us from it. We are lost in endeavouring to get a fixed idea of the magnitude of the starry heavens, even when using as our basis this measurable distance; and the pride which the consciousness of this wonderful discovery raises in us with regard to man's intellect, has its proper antidote in the sense of the inconceivable magnitude of the works of the Almighty.

100. There are two other instances in which it is tolerably certain that the amount of parallax has been pretty accurately measured. The first is for a double star called *α* Centauri, of the first magnitude, in the southern hemisphere, in which all the elements which denote the proximity of 61 Cygni are found existing, in addition to great brightness. The other is the well-known star *α* Lyræ, of the first magnitude, in our own hemisphere. The latter was detected by the Russian astronomer, Struve, about the same time with Bessel's discovery, and by a similar mode of measurement, excepting that he used a wire micrometer, and compared *α* Lyræ with only one star. The former was detected in the first instance by meridian observations made at the Cape of Good Hope by Henderson (Astronomer there from 1831 to 1833), and has since been verified by other observations made by his

successor, the late Sir Thomas Maclear. The resulting parallax of α Lyræ is about two-tenths of a second, but that of α Centauri amounts to very nearly a second of space. Those who have attentively studied our remarks on refraction and other sources of uncertainty as affecting meridional observations, will see that the nature of the evidence proving the existence of so large a parallax for α Centauri is inferior to that for the other two stars; but later determinations have so fully confirmed it that we can no longer doubt that it amounts to about nine-tenths of a second.

101. We will briefly recapitulate a few of our leading remarks on parallax. *Parallax*, generally, is the displacement which a body not infinitely distant suffers by being viewed from the surface instead of from the centre of the earth. It is measurable in the case of the moon by making observations of polar distance at stations, one in a high northern and the other in a high southern latitude, such as Greenwich and the Cape of Good Hope; the base of measurement being the distance of the stations. The results prove that the mean horizontal equatorial parallax (that is, the parallax on the horizon, for a place situated on the earth's equator, at the moon's mean distance) is about 57′; or the moon's mean distance is about 240,000 miles.

102. It has been mentioned that 8″·571 was long the accepted value of the solar parallax as deduced from the observations of the transits of Venus in 1761 and 1769, and that recently several independent investigations have proved that this value is too small. From several series of observations of Mars made at the opposition of 1862, and a careful comparison and discussion of the whole, it results that 8″·85 is the most probable value. Other investigations have more or less confirmed this, which is now used in most of the national ephemerides, and is probably within 0″·02 or 0″·03 of the truth.

103. For calculation of the parallax p to be applied to the zenith distance z of any planet, we have (if r be the proportion which the earth's radius, at the station of observation, bears to the equatorial radius, and P be the equatorial horizontal parallax),

$$\sin. p = r \sin. \mathrm{P} \sin. z,$$

or, with sufficient accuracy,

$$p = r \,\mathrm{P} \sin. z,$$

which, in the case of the sun, becomes

$$p = 8''{\cdot}85 \times r \sin. z,$$

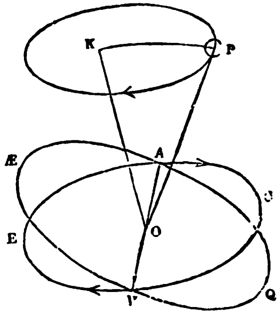
of which a table can easily be formed.

104. Lastly, the distances of the stars can only become known by observations made of them at opposite points of the earth's orbit; and the method which promises and has thus far been attended with most success, is that of measuring their angular distances from other stars probably at a much greater distance. The three stars, 61 Cygni, α Lyræ, and α Centauri, may be presumed with some degree of confidence to have measurable parallaxes amounting respectively to about $0''\cdot3$, $0''\cdot2$, and $1''$.

105. Thus far the displacements of objects which we have been considering have respect only to the local position of the observer on the earth's surface, and to the bending of the rays by which they are rendered visible on coming into the earth's atmosphere. By the correction applied for *refraction* and *parallax*, all the heavenly bodies are referred to the positions in which they would be seen by an observer at the centre of the earth, by means of rays coming to the eye without any deflection. But it is to be remembered that the positions of all celestial objects have been defined by reference to two points—the one, viz., the intersection of the ecliptic and equator, forming the zero point of right ascension; and the other, viz., the vanishing point of the earth's axis produced, forming the zero of polar distance. If, then, these points were fixed, astronomers would have no farther trouble in settling the positions of all the heavenly bodies but such as arise from a purely optical cause which we shall afterwards explain. But the fact is not so. It has been known as a fact of observation for about 2,000 years that the equinox, as it is called, or the point of intersection of the ecliptic and the equator, moves backwards, that is, from east to west, along the ecliptic with a motion amounting to about $50''$ per year, and that the pole of the equator is thus carried round the pole of the ecliptic in the same direction; so that it would describe a complete circle about that pole in about 26,000 years. Before, then, we can fix the places of the planets for definite times, or form catalogues of stars for definite epochs, it is necessary that we should be able to trace the cause, and to calculate the amount of the corrections due to this phenomenon. Now this we cannot do without referring to the principles of physical astronomy, and treating, though briefly, of the way in which the revolving protuberant matter at the earth's equator is affected by the sun and moon's action. But it will, perhaps, conduce to clearness of conception of this difficult

subject if we first consider the phenomena of precession and nutation in relation to their effects derivable from observation.

106. We have said that the right ascensions of all stars are measured from the vernal equinox; the position of this point being determined by observing, with the mural or transit circle, the polar distances of the sun a little before and a little after he crosses the equator, both at the vernal and the autumnal equinox. The polar distances of the stars are also observed by means of the circle. Now, by knowing the inclination of the equator to the ecliptic or the plane of the sun's motion (which is, in fact, the sun's distance above or below the equator at the summer and winter solstices, when he attains his highest and lowest points respectively in the heavens), the positions of the stars can be calculated with reference to the ecliptic and the same equinoctial point; that is, their latitudes and longitudes can be calculated. By this process it is found that for all stars whatever, observed at distant intervals of time, the latitudes are sensibly constant, but that the longitudes of all have a yearly increase of at least 50″. Of course we may here apply the same reasoning which we have before used with regard to the apparent diurnal motion of all the stars from east to west, and conclude that this common motion to all in the same direction is not real, but apparent, arising from a uniform *retrogression* along the ecliptic of the point of reference, that is, of the equinoctial point. This *retrogression* is called the *precession* of the equinoxes, because its motion being in the direction of the diurnal motion, it brings the intersection of the ecliptic and equator on any meridian sooner each succeeding year than it would have otherwise come, and makes the interval between a season of one year and the corresponding season of the next shorter than it would otherwise be. But the student must remember that the point in question goes *backwards*, and not *forwards*, upon the ecliptic. In the accompanying figure, let A E V C and A Æ V Q represent the plane of the ecliptic and equator, and *K* and P their respective north poles (O K and



O P being at right angles to them), V the vernal and A the autumnal equinox; then the points V and A regress along the ecliptic in the direction of the arrow points, and, of course, carry the point P in a small circle round K in the direction also indicated by the arrow point. The pole of the equator, in its progress round that of the ecliptic, will move away from certain stars which it has passed in its course, and approach others. Thus, at present it is still approaching the remarkable star α Ursæ Minoris (Polaris), but after a time it will recede from it, and after the lapse of a great many ages, it will approach very near to the great star in the constellation Lyra, which will then be the polar star to astronomers in the northern hemisphere.

107. But though we have described the effect of the precessional motion by means of the small circle, which, in its mean effect, it causes the pole of the equator to describe round the ecliptic, yet this is true only approximately. If we were to lay down the curve actually described, it would be an irregular line approaching to a circle, and with its irregularities recurring again and again, at intervals of about nineteen years. In fact, the true state of the case may be accurately enough represented by imagining a point P to be carried uniformly round, while another point (the real pole) is describing round this a minute ellipse, whose longer axis, about $18\frac{1}{2}''$, is directed towards K, and the shorter axis, about $14''$, is at right angles to it. These variations of the mean precessional effect are called *nutation;* and, of course, affect the places of all bodies referred to the pole and to the equinox, and must rigorously be taken into account in all calculations for reducing them to any fixed epoch.

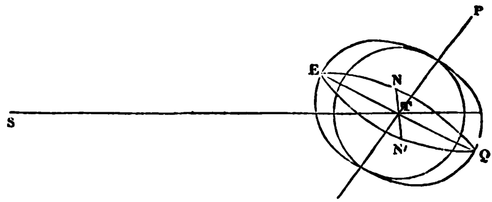
108. We will now endeavour to give some idea of the physical cause of this most interesting phenomenon, whose observed effect was first detected by Bradley, and given nearly in the shape in which we have put it above.

109. Our readers have, doubtless, some notions of the theory of gravitation. If they have not, it is better to omit for the present any attempt at understanding what follows. The law of universal gravitation is simply this, that every particle of matter in the universe gravitates towards every other particle, or attracts and is attracted by every other particle, with a force varying inversely as the square of the distance. This law, simple as it is, will account for all the wonderful phenomena which are the objects of our speculation and research in astronomy. By it we can account for

the spheroidal figure of the earth and planets, and explain the laws of their motions in their orbits; and by it we can calculate with wonderful accuracy the place which any planet will occupy in the heavens at any assigned period. By the application of this law we can trace out in the heavens the path of so filmy and vaporous a body as a comet, through whose densest parts the smallest stars are visible; and astronomers have, in many instances, predicted their return, after the description of orbits of almost inconceivable magnitude. The tides of the ocean also rise and fall in accordance with the law, and, independently of the local circumstances which affect them at individual places, afford one of its most beautiful exemplifications. Lastly, the phenomena of precession and nutation now before us admit of a full and perfect explanation, though we can promise to give, in a popular form, only a very vague notion of them.

110. The earth, as you are aware, is a spheroid of revolution rotating round its smaller axis, whose ellipticity, that is, the ratio of the difference of the axes to the major axis, is about $\frac{1}{300}$. Now the axis of revolution is inclined at an angle of about 23° 28′ to the axis of the ecliptic; and, consequently, there is a small ring of protuberant matter, or meniscus, above the sphere whose diameter is the minor axis, inclined at the above angle to the ecliptic, and divided into two equal parts by it. Imagine this ring of matter to revolve independently of the earth, and in the same time, and to fix the ideas, imagine the state of things at the summer or winter solstice, when the angular distance of the sun from the earth's equator is greatest. In this case, the effect of the sun's disturbing action (that is, the difference between the pulling force on the centre of the earth and on any particle of the meniscus) will be such as to bring it towards the ecliptic, and, if the motion of revolution were to cease, it would ultimately pull it into coincidence with that plane; but, on account of its rotation, the effect will be so far modified that the inclination in a whole revolution will remain unaltered, but the points N N′ (Fig. p. 58), where the plane E Q cuts the ecliptic, will regress. In fact, each point being pulled towards the ecliptic, will reach it sooner than it would otherwise have done, or the motion of the line N N′ will be in the contrary direction to that of the motion of rotation. Now, in the case of nature, this meniscus is solidly joined to the earth, and therefore whatever motion is given to the ring *must be communicated* to the whole body; and thus, on

account of the large mass of the earth which the ring has to drag with it, the motion will be exceedingly diminished. The effect, however, will be of the same kind; that is, the points of intersection of the ecliptic and equator will upon



the whole retrograde. If we consider what will be the state of things at the equinoxes, we shall readily see that the sun being then in the plane of the earth's equator, and consequently there being no force to pull the protuberant matter out of its natural position, the retrogression will be nothing; and in the same manner, and for all time intermediate to the equinoxes and solstices, the effect will be also intermediate.*

111. Thus far we have considered only the effect of the disturbing action of the sun, which, on account of its immense distance, produces but a small part of the observed retrogradation. The moon, though her mass is not $\frac{1}{30,000,000}$ part of the sun, produces, by being so near to us, a much more serious effect. It is very evident that her action will be of the same character as that of the sun, though the changes will be very much greater, on account of her wider excursions above and below the equator, and also because the plane of her own orbit is not fixed upon the ecliptic, but itself retrogrades, so as to go round the whole circle in a backward direction in the space of about $18\frac{3}{4}$ years. Now, during half of this period, the position of the nodes of the lunar orbit is such that its plane is but little inclined to the earth's equator, and therefore the precessional effect will be small; but during the remaining half the inclination is considerably greater, and the lunar precession becomes thus proportionally larger. These inequalities of precession, caused separately by the sun and moon, are called *solar* and *lunar* nutation, on account of the irregular motions which they produce in the poles of the heavens, and, consequently, in

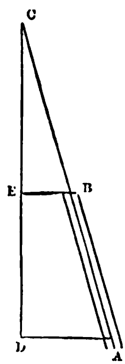
* See *Airy's Popular Astronomy*, page 175.

the polar distances of stars. The first evidently has for its period a solar year, or time of revolution of the earth round the sun; the second depends upon the place of the moon in her orbit, and also upon the time of revolution of her nodes, and therefore requires for its expression two terms, the one depending upon the moon's longitude, and the other upon the longitude of the node.

112. In all that has been said thus far, it has been assumed that the *plane* of the ecliptic is absolutely fixed in space, but even this is not the case, since the relative orbit of the sun and earth suffers also disturbances by the action of the larger planets, which require also to be taken into account. At present we are not in a condition to enter more largely upon this subject, and the general explanation of precession is not affected by it.

113. By application of corrections derived from the theory of precession and nutation, we are enabled now to represent the places of the stars for any epoch, as correctly as if the points of reference were absolutely fixed; yet we have still one correction to make, depending upon a phenomenon of a totally different character: we mean the phenomenon of the aberration of light. Römer discovered, by means of the eclipses of Jupiter's satellites, when observed at different distances of Jupiter from the earth, that light was propagated with an immense, though measurable velocity, so as to describe the radius of the earth's orbit in about $8\frac{1}{3}$ minutes; but it was reserved for Bradley to show by observation, that this progressive motion of light, combined with the motion of the earth in her orbit, would produce an apparent displacement of every object in the heavens; throwing it apparently a little behind the place which it ought, according to theory, to occupy. The casual experiment by which Dr. Bradley was first led to the idea of the theory of aberration is instructive, not only in showing the process by which a great mind arrived at the explanation of this most important phenomenon, but as giving a really simple and intelligible elucidation of it. He was in a wherry on the Thames, which had a vane for observing the direction of the wind at the top of the mast. The boat being stationary, he observed by this vane the direction of the wind, but it appeared to him that when the boat was again in motion the direction immediately changed. The boatmen were themselves familiar with the phenomenon, but were unable to explain it; and, by reflection, Bradley was *soon enabled* to see that the change of direction must

be not real, but apparent, and depending upon the unthought-of motion of the observer. Several other illustrations may be given, of which the most usual is that of the direction of rain-drops falling upon a person as he walks. If the drops fall vertically, and he be walking with any considerable velocity, they will strike him on the face, as if they came towards him in an oblique direction. An ingenious illustration is given by Airy, in his "Popular Astronomy." Imagine the side of a ship in motion to be pierced by a shot from a battery which she is passing, which goes out at the other side. It is evident that the point of the off-side of the ship at which the shot goes out will be farther astern than the hole made on entering the other side; and the sailors, if they did not attend to the motion of the ship, would imagine that it had passed through in an oblique direction. We will take one more illustration, which will enable us to see still more clearly the law according to which the effect of *aberration* must be calculated.

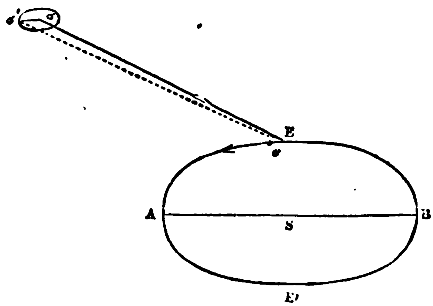


114. Let A B be a tube, making a fixed angle with the horizon, but carried forward horizontally in the direction A D, with a velocity represented by A D. Let now a body fall from C, with a velocity represented by C D, at the same time that the tube starts from A; then it is evident (by similar triangles) that when the top B of the tube has arrived at E, the body will also have fallen to E, or will enter at the top of it, and, the ratio of the velocities still remaining the same, will proceed within it, through its whole length, without striking the sides. If, also, an observer at A were looking up the tube, the body would appear to fall in the direction C B A, instead of the vertical direction. In this instance, then, the effect of *aberration* is the angle C, which may be calculated by the formula,

$$\text{Tan. C} = \frac{\text{D A}}{\text{C D}} = \frac{\text{velocity of observer}}{\text{velocity of falling body}}$$

Let us now apply this analogy to the case of an observer on the earth's surface, looking at a star, the velocity of light being supposed known, and being in round numbers to that of the earth in its orbit nearly as 10,000 to 1, or as unity to *the tangent of an arc* of $20''\cdot5$. Let σ be the place of any

star, and E that of the earth at any time, describing its orbit round the sun, S, in the direction E A E′ B; E e, a small arc of the orbit described in the unit of time. Then, if a space be set off on E σ equal to that traversed by light in the same



time, and the parallelogram be completed, of which these spaces are the sides, its diagonal will be in the direction E σ', of the apparent position of the star. The effect of this displacement will be to make each star in the heavens apparently describe a small ellipse round the true place unaffected by aberration, and the axes of this ellipse will depend upon the position of the star with regard to the ecliptic; that is, on its latitude. If, for example, the star were in the ecliptic, the whole displacement would be in this plane, the effect on the latitude of the star being nothing; but, if the star were situated at the pole of the ecliptic, the curve described round its mean place would be a circle with an angular radius equal to $20''\cdot5$; and generally, the axes of the ellipse will be in the proportion of unity to the sine of the latitude.

115. Without going into details, for which, in fact, we have not space, the intelligent reader will readily understand, from the principles already laid down, that the apparent displacement which every star experiences with respect to the ecliptic can be calculated, and the position of that plane with regard to the equator being known, the small corrections in right ascension and polar distance can also be computed. Conversely, by judicious observations, continued throughout every period of the year, of stars situated near the pole of the ecliptic, where the effect of aberration is the greatest possible, it is plain that the axes of the *aberration ellipse* will be found, and the constant quantity (or *numerical multiplier* necessary for the computation of its effect upo

every star) of its expression will be found. It was by observations of the star γ Draconis, which for Greenwich passes the meridian very near the zenith, that Bradley detected this important phenomenon. The right ascension of this star is nearly 18 hours, and its north polar distance nearly equal to the colatitude of Greenwich. It lies, therefore, very nearly in the plane of the great circle joining the poles of the ecliptic and equator (called, technically, the solstitial colure), and about 15° from the pole of the ecliptic. If, then, the reader has carefully attended to the preceding explanation, he will see that when the earth is in the autumnal equinox, and therefore moving parallel to the colure, the effect of aberration will be apparently to raise the star above the ecliptic, and therefore to bring it nearer to the north pole of the equator by the quantity $20''\cdot5 \times \sin. 75°$ ($= 20''\cdot5 \times \sin.$ star's lat.); but that when the earth is at the vernal equinox, the effect will be to increase the distance from the pole by about that quantity. If, then, the observations of polar distance made at these periods be corrected for refraction, precession, and nutation, their difference will amount to about $41'' \times \sin. 75°$, or to nearly $40''$.

116. M. Struve, the Russian astronomer, by observations made a few years ago, has definitively fixed the constant of aberration at $20''\cdot445$, which, he believes, does not differ $0''\cdot011$ from its true value; and hence the velocity of light is known with very great accuracy, and the time taken to traverse the mean radius of the earth's orbit will be $8^m\ 17^s\cdot78$ of mean time. The author of this little book has, by the discussion of a series of observations of γ Draconis made with the reflex zenith tube at Greenwich, found the value $20''\cdot34$ for the constant.

117. The effect of aberration on the places of the planets differs from that on the places of the stars in consequence of their motion in their own orbits. On this account it happens that they are seen by rays coming from a point different from that which they occupy when the observation is made. It is evident, in such cases, that the effect of aberration referred to any planes whatever will depend on the *relative* motion of the earth and the planet, that is, on the geocentric motion of the planet, and on its distance from the earth. Let, for instance, D be the distance of the planet from the earth; then the time in which light traverses this space is $8^m\ 18^s \times \frac{D}{R}$, where R is the radius of

the earth's orbit, supposed circular. This time is technically called the *aberration-time*, and the geocentric motion of the planet being known, the space through which it will move in the above time, whether in right ascension or declination, is the correction for aberration. The most convenient way of computing the *apparent* places of the planets, that is, their places affected by aberration, is to subtract the *aberration-time* from the time for which their places are required, and to consider the remainder as the time for which the computations are to be made.

118. There is still one effect of aberration to be considered, viz., that arising from the earth's diurnal rotation on its axis from west to east. This effect is so small as not to be appreciable by observation, but it produces an error in the places of all objects observed with the transit instrument (throwing them too far east, or causing them to come to the meridian too late) of the same kind as the error of collimation, which is necessary to be taken into account. Its amount is easily calculated.

119. Let Greenwich be the station of observation, in north latitude 51° 29′; then the space through which the earth's equator will be carried in the time t seconds will be

$$\frac{t \times 2r \times 3{\cdot}14159}{24 \times 60 \times 60} = rt \times \frac{2}{27500} \text{ nearly,}$$

where r = the earth's equatorial radius; and the space through which the parallel at Greenwich is carried in t^s is

$$2rt \times \frac{\cos. 51^\circ\ 29'}{27500};$$

but the space through which light moves in t^s

$$= \frac{t}{497} \times \text{R (where R = radius of earth's orbit).}$$

Hence,

$$\frac{\text{velocity of rotation at Greenwich}}{\text{velocity of light}}$$

$$= \frac{2r}{\text{R}} \times \frac{497}{27500} \times \cos. 51^\circ\ 29'$$

$$= \frac{8000}{92000000} \times \frac{497}{27500} \times \cos. 51^\circ\ 29' \text{ nearly,}$$

$$= \frac{1}{1021790} \text{ nearly.}$$

120. This represents the tangent of the angle of aberration in this instance, and the corresponding arc is $0''\cdot202$. Every star, therefore, comes to the meridian too late by the time of its motion over this arc, and requires a correction in time $= -\dfrac{0\cdot202}{15 \sin. \text{N. P. D.}}$. The error itself is, however, in practice incorporated with the error of collimation.

121. We are now enabled by the application of the corrections due to refraction, parallax, precession, nutation, and aberration, to represent the places of the stars as they would be observed by a spectator placed at the earth's centre, supposed fixed in space, with no atmosphere causing displacement, and referred to fixed points and a fixed plane of reference. It is evident, however, that the corrections required for precession, nutation, and aberration will be computed from formulæ necessarily of some complexity. We are indebted to the illustrious Bessel, in the first place, for reducing the formulæ to a shape admitting of easy computation, in every case, by separating the terms of their expressions into double sets of factors, the one set containing only such quantities as depend on the time, such as the date of the observations, the position of the node of the lunar orbit, and the places of the sun and moon, on which the nutation and aberration depend; the other set involving only such quantities as depend on, or are functions of, the star's right ascension and declination.

122. The logarithms of the first set of quantities are given in the Nautical Almanac for every day of the year, under the designations A, B, C, D, and the large catalogue of stars published under the authority of the British Association gives for every star included in it the values of the logarithms of the second set of quantities for both R. A. and N. P. D., for the epoch 1850, under the designations a, b, c, d and a', b', c', d'. The whole correction to be applied to the mean place of a star to obtain its apparent place for any day required is—

For Right Ascension . $\text{A}\,a + \text{B}\,b + \text{C}\,c + \text{D}\,d$
For N. P. D. . . . $\text{A}\,a' + \text{B}\,b' + \text{C}\,c' + \text{D}\,d'$.

CHAPTER IV.

OF THE MOTION OF THE SUN IN THE ECLIPTIC, ETC.

123. In the preceding chapter it has been our object to bring together, so as to exhibit in one point of view, all the corrections which are necessary to be made before the true place of a celestial object can be found from observations made at the surface of the earth. In doing this, however, we have been obliged to anticipate in a slight degree, or to assume the reader's acquaintance with, a few of the leading facts of the solar motion, as well as some familiarity with the plane in which that motion is apparently performed. We have in the same manner assumed, in some degree, his familiarity with the motion of the moon round the earth. But, in fact, all we have required to be admitted is, that the sun *apparently* moves round the earth, or the earth *really* moves round the sun, in a nearly circular orbit, described in a plane, sensibly fixed, called the ecliptic. We have also assumed in like manner for the moon, that she revolves round the earth in a nearly circular orbit; but that the plane of her orbit, which has a small inclination of about 5° to the ecliptic, has a retrograde motion on the ecliptic by which it is carried completely round the circle in the space of nearly nineteen years.

124. It will be our object in this chapter and the following to treat of the motions of these luminaries a little more specifically, and at the same time to introduce such remarks on the theory of gravitation as will enable the reader to obtain an idea, however vague and imperfect, of the laws according to which the orbits are described, and of the perturbations to which they are subject. In the present chapter we confine ourselves to the investigation of the solar orbit; to the consideration of the various measures of time

used by astronomers; and, finally, to an account of the knowledge which has been acquired concerning the physical constitution of the sun.

125. The portion of the heavens in which the sun's *apparent* orbit is performed was called by the ancients the *zodiac;* and the great circle formed by the intersection of the plane of his orbit with the sphere of the heavens was divided by them into twelve equal portions or signs, to which were given, from the constellations through which the sun passes, the following names:—

Aries	Leo	Sagittarius
Taurus	Virgo	Capricornus
Gemini	Libra	Aquarius
Cancer	Scorpio	Pisces.

126. About 4,000 years ago, the position of the vernal equinox, that is, of one of the points of intersection of the ecliptic or sun's path with the equator, coincided with the constellation Aries; but on account of the precession of the equinoxes, this point is now in the constellation Pisces. It is, however, customary with astronomers still to call the point of the spring equinox the *first point of Aries.* No confusion arises from the term, but great inconvenience is frequently experienced by an attempted change of nomenclature.

127. We have already, without alluding to any theory of the solar motion, shown how the mean distance of the sun, or the solar parallax, has been found by observations of the last transit of Venus across the disk, and by observations of Mars when nearest to the earth, but we have not made any reference to the variations of his distance from the earth in the annual circuit. Now, if our readers would take the trouble to consult the Greenwich observations for any one year, and look at all the measures of the sun's diameter which have been made with the mural circle, they would not fail to perceive that in the course of the year the variations of the measures are far greater than can be attributable to errors of the observations, though, from the fluttering, badly-defined nature of the borders of the disk, these frequently amount to several seconds of arc. If, however, any one would give himself the trouble to take the mean or average of the measures of the diameters on several neighbouring days, and thus divide the whole series into groups, he would observe a *very conspicuous* law in their variation. For example, he

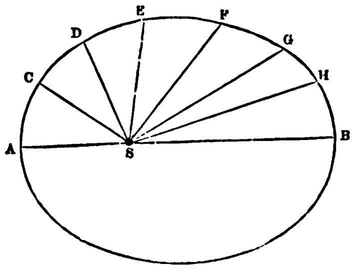
would find the measures smallest about Midsummer, and largest at the end of December, and between these times he would find a steady, uniform increase; while from January to the end of June the decrease would be equally uniform. Now the object observed being the same, this proves that the distance of the sun is least in winter, and greatest in summer, and that the variations of increase and decrease are tolerably uniform.

128. A tolerable notion would thus be formed of the general shape of the orbit. It would be found to be not quite circular, but the extreme variations of distance would show that it does not differ much from a circle. In the year 1868, for example, the largest diameter given in the "Nautical Almanac" is that for the end of December, viz., 32′ 36″·4, and the smallest is that for the end of June, viz., 31′ 32″·0. The difference of these compared with the mean diameter is about $\frac{1}{30}$ part of the whole; and this, therefore, is the proportion in which the greatest distance of the sun from the earth exceeds the least. We might thus suppose, without further reasoning, that the earth moves round the sun, or the sun apparently round the earth, in an orbit slightly oval or elliptical; and a trial of this theory with observations of the diameters would show whether an exact ellipse is described.

129. It was, in fact, proved by Kepler, about three centuries ago, that not only the earth, but all the large planets describe ellipses about the sun, that body being in one of the foci of each of the ellipses. This law of the planetary motions is known by the name of *Kepler's first law*. The excentricities of these ellipses are different, and appear to be totally independent of each other; the planes of their orbits are also different, but are all included within a small angular distance from the ecliptic (about 10°), called the zodiacal limits; and, finally, the directions of their major axes are different. Still, all the orbits are ellipses described in the same direction from west to east, in planes round the sun as a common centre.

130. Again, if we were to proceed really to construct the curve of the solar orbit by assuming, as in the figure, the point S as the focus round which the sun appears to move, and, after calculating the sun's longitudes, from the observed right ascensions and declinations at times corresponding to those at which the diameters or distances proportional to them were observed, laying off angles C S D, D S E, E S F,

&c., equal to these differences, and lines C S, D S, E S, &c., inversely proportional to the observed diameters, we should not only find that the curve was sensibly elliptical, but that another law of the solar motion would become evident. We should find, in fact, that the velocity of the sun when near his shortest distance (*perigee*) S A is considerably greater than when near the greatest distance (*apogee*) S B, and that, being greatest at A, the velocity continually decreases till he arrives at B, when it is least; it then increases again during the remainder of the year till it is greatest at A. By comparing, for instance, the sun's increase of longitude in equal small times when near A and when near B (which gives the measure of angular velocity), we should find that the velocity at A would exceed that at B by about $\frac{1}{15}$ part, while the distance S B exceeds S A by about $\frac{1}{30}$ part. For instance, taking numbers from the "Nautical Almanac" for 1868, we find that the daily increase of the sun's longitude at the end of December is about 1° 1′ 8″, but that in June it is about 57′ 12″. The difference of these is 3′ 56″, which, compared with the mean daily increase 59′ 10″, gives the fraction $\frac{236}{3550}$, or $\frac{1}{15}$, corresponding to the ratio which has been previously assumed. The same is true in every other part of the orbit, that is, the increase of velocity is twice as great as the decrease of distance. Now, we might readily prove from this that the sun's angular velocity must be in general inversely proportional to the square of the distance. For, let r be any distance from the earth, and v the corresponding angular velocity, then if v varies $\frac{1}{r^2}$, $r^2 \times v$ must be a constant quantity. Let now $r + x$ and $v + y$ be the radius vector and velocity at another time of the year. Then the value of $(r + x)^2 \times (v + y)$ must be equal to $r^2 v$, because this quantity does not vary by the corresponding variations of r and v.



Hence, $$r^2 v + 2 r v x + r^2 y = r^2 v,$$

neglecting the small quantities $x^2 y$, $2 r x y$, $x^2 v$.

Hence, $2vx = -ry$; or, $\frac{y}{v} = -\frac{2x}{r}$.

That is, the increase of v compared with v is twice as great as the decrease of r compared with r. Conversely we may assume, that if the latter proposition be true, the quantity $r^2 v$ must be constant; or the velocity varies in the inverse proportion to the square of the distance or radius vector. Now this law, which belongs to all the planetary motions as well as to the sun, was also discovered by Kepler, and under the name of the *equable description of areas* is known as Kepler's second law. It may be distinctly announced as follows:—The areas swept out by the radii vectores of the planets (that is, by the lines drawn from them to the sun) are proportional to the times of their description; or, equal areas are described in equal times.

131. It will be well, in this place, to enunciate Kepler's third law of the planetary motions, though we are rather anticipating. He found, by a most laborious comparison of the planets' distances from the sun with their times of revolution, that a very simple and general law of connection subsisted between them. The law simply enunciated is this, "that the squares of their periodic times of revolution are to each other as the cubes of their mean distances from the sun or the semi-axes major of their orbits." This is the law which we have before adverted to in the discussion of the solar parallax. We see by it that if the distance from the sun of any one planet be known, the distance of all the others can be found by simple proportion. Suppose, for example, that the mean distance of Mars be a, and its observed time of revolution t. Let the time of revolution of the earth round the sun be T, and the mean distance required x. Then, by Kepler's third law, $\frac{x^3}{a^3} = \frac{T^2}{t^2}$.

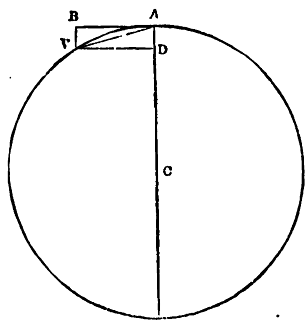
Hence, $x = \left(\frac{T}{t}\right)^{\frac{2}{3}} \times a$.

And the same rule will apply to any of the other planets.

132. Now the whole of the above laws are simple mechanical consequences from the universal law of gravitation, to which we will now devote a few words. The sun, considered as a spherical body, exerts precisely the same influence upon a planet, considered as a spherical body, as if

the whole mass of the sun and of the planet were concentrated at the centre of each. If this be assumed (the proof is by no means elementary or easy, though it *has* been proved by mathematicians), the application of the theory is simple. A point or centre of force of a certain energy attracts towards it another point moving at a given time with a definite velocity, in a direction *not* exactly *towards* nor exactly *from* the centre, with a force inversely proportional to the square of the distance; what curve will the body describe in consequence? This is the problem to be resolved, and Newton first demonstrated, and other mathematicians have since proved the same in various ways, that in all cases whatever the attracted body will describe a conic section, that is, a curve lying in one plane which is either a circle, an ellipse, a parabola, or an hyperbola. The particular curve described by the planet will depend upon the circumstances of the motion, that is, upon the direction of its motion with regard to the line joining it and the sun, and upon its velocity, at any known part of its orbit. For instance, if when the earth is moving with its greatest velocity, that is, when it is at the least distance from the sun and its direction of motion is at right angles to the radius vector, the velocity should be suddenly lessened in a small degree, it might describe a circle instead of its present elliptical orbit. If, again, the velocity were to be increased to a certain amount, it might never return towards the sun, but describe a parabola; and, finally, if the velocity were still farther increased, it would describe an hyperbola. These results are arrived at by an extension of the same kind of reasoning as is used in determining the laws regulating the fall or the motion of bodies near the surface of the earth, for which we would refer to the "Rudimentary Treatise on Mechanics." A stone, for instance, thrown in any direction but the vertical will return to the earth after describing a parabolic curve. Now in this case it is manifestly impossible to give to the stone a sufficient velocity to enable it to clear the earth's surface, and, even if it were practicable to give it a sufficient initial velocity, the resistance of the air (varying as the square of the velocity) would so instantaneously and enormously diminish it as to render it useless. Also, the whole range of the stone is so small, compared with the earth's surface, that throughout it gravity may be supposed to act in parallel lines and with a constant *amount of force.* Hence the problem becomes very much

modified. But, if we imagine the stone thrown from a *very* great height above the earth's surface, in an oblique direction to the line joining it and the earth's centre, it is still the *same* problem which we have to solve, only the data have become more complicated. The force, in this instance, does not act in parallel lines, but towards a centre, and it is not a constant but a varying force, depending upon the distance from the centre of the earth. But to fix the reader's ideas, we will take the simplest case of possible planetary motion, viz., that wherein the body, by the influence of a central force, is made to describe a circle round the centre, and we will find what the law of the force is in this instance.

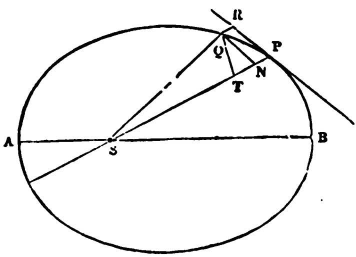


183. Suppose a body A to revolve in a circle round a centre of force C. At every point it is moving in the direction of the tangent at that point, and, if the force were suddenly to cease, it would go on, with a constant velocity, in that direction. Suppose, then, that if left to itself it would describe the space A B in a given small space of time; and suppose, also, that the force in the direction A B would draw it through the space A D in the same time. Then, if the parallelogram A B V D be completed, V will be the actual place of the body, which is, by hypothesis, in the circumference of the circle. Hence A D or B V $= \frac{\text{A V}^2}{2\,\text{A C}}$. If, now, A V and B V be indefinitely diminished, A V will become equal to the arc A V; and, if the given time be taken as the unit of time, will represent the velocity of the body in the curve. Also, B V, being the space through which the body is drawn in the unit of time, will represent the half of the accelerating force (F). Hence, if V be the velocity and R the radius of the circle, we have $F = \frac{V^2}{R}$, or, the velocities of bodies describing circles, if the force be constant, will be as the square roots of the radii of the circles. For instance, if a stone attached to a string be whirled round so as just to be retained in a circle, as the string is lengthened the velocity

in the curve will be increased in the duplicate proportion. But, if we wish to know how the angular velocities vary, putting α to represent it, we have $V = R \times \alpha$; or $F = \alpha^2 R$.

184. Hence, the tension of the string remaining the same, the radius varies inversely as the square of the angular velocity. But if the angular velocities be constant, or the circles be described in the same time, then the tension of the string will be increased in the simple proportion of the radius.

185. Similarly, if we wished to find according to what law of force a body might describe an ellipse round a centre of force situated in one of the foci, we should use similar reasoning.



186. Thus let S be the centre of force; P the position of the body at any time, moving in the direction of the tangent, P R with a certain velocity denoted by P R; P N or R Q the space through which the body would be drawn by the action of the force in the infinitesimally small time T; P R Q N being a parallelogram. Then, if F be the force which deflects the body through the space R Q, we have, by the second law of motion, $Q R = \frac{1}{2} F T^2$. But, if A be the constant area described in the unit of time, the area Q S P will be A $\times$ T. This area is, however, ultimately equal to $\frac{1}{2}$ S P $\times$ Q T, Q T being perpendicular to S P.

Hence $T = \dfrac{Q T}{2 A} \times S P$.

Hence F, which is ultimately equal to the limiting value of $\dfrac{2 Q R}{T^2}$

$$= 2 Q R \times \frac{4 A}{Q T^2 \times S P^2}$$

$$= \frac{8 A^2}{S P^2} \times \text{limiting value of } \frac{Q R}{Q T^2}.$$

187. To understand what is meant by the limiting value of $\dfrac{Q R}{Q T^2}$, imagine the point Q to approach towards P, and at

length to reach it; then, though each of the quantities Q R and Q T^2, taken separately, ultimately vanishes, yet their ratio continually approaches nearer and nearer to some definite value, which can be found for any particular curve under consideration. For the ellipse this ratio is a constant quantity, that is, it is the same for every point of the curve, and hence the force varies as $\frac{1}{\mathrm{S\,P}^2}$.

138. The foregoing considerations will show the nature of the investigations by means of which Newton traced his way to the true theory of the planetary motions. Assuming that the planets were kept in their orbits or made to describe certain curves in one plane by a force directed towards the sun, his object was first to find what must be the law of force by which this could be effected. Kepler has proved that the orbits were ellipses having the sun in one of the foci, and Newton easily proved, in the way we have explained, that the force must be inversely proportional to the square of the distance. He discussed likewise the laws of force for other curves, and other centres. For circles his discussion is nearly as we have given it; and, if an ellipse were described round the centre, he finds that the force must vary directly as the distance. It is evident, therefore, that, as far as the planetary motions are concerned, the force must be that of the inverse square of the distance, for no other law of force can be reconciled with Kepler's first law derived from observation.

139. Again, he found that for any law of central forces whatever, the areas described must be proportional to the times; and this latter fact being previously known as the result of observation, in the description of the orbits of the planets round the sun, it is plain that the force by which the planets are kept in their orbits is directed to the sun. This proposition was therefore to be proved before the laws of force round a fixed centre could be considered, and thus in Newton's "Principia" it forms the first proposition, though we have taken it according to the order of Kepler's laws.

140. Lastly, Newton found that the time of his description of any elliptic orbit round a centre of force varying inversely to the square of the distance would vary in what is called the sesquiplicate ratio of the semi-axis major directly, and of the square root of the mass of the attracting body inversely. Thus, if T be the time of revolution, a

the semi-axis major, and μ the mass, $T = \dfrac{2\pi a^{\frac{3}{2}}}{\sqrt{\mu}}$, where $\pi = 3{\cdot}14159$. This we can prove easily enough in the case of the circular orbit before discussed. Taking the equation $F = a^2 R$, let T be the periodic time, then $T \times a = 2\pi$, and $F = \dfrac{\mu}{R^2}$ (by hypothesis of the force varying according to the inverse square of the distance).

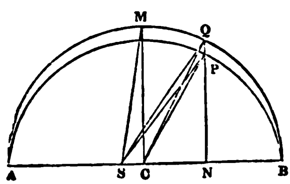
Hence,
$$\frac{\mu}{R^2} = \frac{4\pi^2}{T^2} \times R$$
$$\text{or, } T^2 = \frac{4\pi^2}{\mu} \times R^3,$$

so that
$$T = \frac{2\pi R^{\frac{3}{2}}}{\sqrt{\mu}};$$

and this expression is equally true in the case of an elliptic orbit, and is, in fact, the symbolical enunciation of Kepler's third law.

141. Having thus discussed the simplest of the features of the theory of gravitation, and shown how it can be proved that Kepler's observed laws are some of the simplest consequences of it, we will proceed to show in what manner the motion of the sun in longitude can be calculated, and to exhibit the principles of the construction of the Solar Tables.

142. Let A P B be the half of the elliptic orbit of the earth described round the sun at S, a focus of the ellipse. Upon A B describe the semicircle A Q B. Let P be a position of the earth at any time, and draw the line Q P N perpendicular to A B. Join S Q, S P, C Q, C P. Imagine now a body to describe the circular orbit A Q B in the same periodic time that the earth describes its elliptic orbit, and let both start together from A, the *perihelion;* also when this body is at M, let the earth be at P; the latter having got beyond the former on account of its greater



angular motion near the perihelion. The angle A C M is called

the *mean anomaly*, and A S P the *true anomaly*. If, then, the relation between these angles can be expressed, that is, if the *true* anomaly can be expressed in terms of the mean anomaly, the earth's real motion or the sun's apparent motion in longitude is known. For, suppose the time taken by the earth in moving from A till it returns to it again be called P, and the time of describing the angle A C M be called T; then, since the circle A M B is described uniformly, we have (if angle A C M = M),

$$\text{M} = \frac{\text{T}}{\text{P}} \times 360^\circ;$$

and, therefore, the true longitude, if it can be expressed in terms of M, can be calculated. Now this can be done by means of an infinite series in terms of the excentricity of the orbit, but it is usual with astronomers to use an intermediate angle A C Q, called the *excentric anomaly*, to effect this development.

143. In fact, the mean anomaly can be expressed very simply in terms of the excentric anomaly, and the true anomaly can also be so expressed, and, for the benefit of such of our readers as are conversant with trigonometry, we will give the equations connecting these three quantities, as our reasoning will thus be rendered clearer.

If m, u, and v be respectively the *mean*, the *excentric*, and the *true* anomaly, and e the excentricity of the orbit, then

$$m = u - e \sin. u;$$

$$\text{and } \tan. \tfrac{1}{2} v = \sqrt{\frac{1+e}{1-e}} \tan. \tfrac{1}{2} u.$$

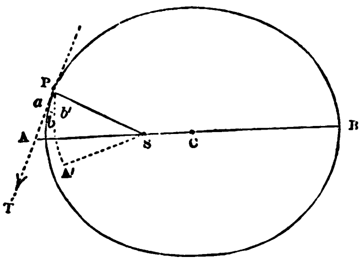
144. We should be going too far beyond the limits of an elementary treatise if we attempted to show how, by means of the above equations, v is expressed in terms of m. It is sufficient to say that it can be so expressed in a series whose first term is m, and that the other terms, involving powers of e and sines of multiples of m, are easily calculable, because e is for all the planetary orbits very small. We get then an equation of this shape—

$$v = m + \text{E},$$

and this latter term is calculated for each planet in extensive tables *with the mean anomaly* for the argument, and is

called the *equation of the centre*. This is the first of the *equations* or *inequalities* in the computation of the longitude of the sun or a planet, which is to be taken into account, and, if the orbits of the planets were strictly elliptical, it would be the only one. But, as we shall see presently, the action of the other large planets disturbs not only the plane of the orbit of any one of them, but also the position of the body in the orbit, and other corrections, called *perturbations*, must be applied to its longitude computed from the elliptic theory, before the *true* longitude can be obtained by addition of the longitude of the perihelion or aphelion to the true anomaly.

145. There is one disturbance of the solar orbit which we shall have occasion to mention before proceeding further, and that is the progressive motion of the *apogee* or *perigee*, or the points of greatest and least distance from the earth, and as this is common to the other planets, we will take this opportunity of saying something of its physical cause.



146. Let P be a position of the earth, or other planet near the perihelion A, and imagine that at P the force in the direction P S is suddenly increased by a small quantity, which soon afterwards ceases. Take P a in the direction of the motion at P to represent the velocity, and a b parallel to P S to represent the deflecting force at P in the undisturbed orbit. Take also a b' to represent the increased deflecting force. Then it is plain that the planet will be made to move in a curve such as P b' A′ lying within P b, and making at P a more acute angle than S P T with S P. With regard to its point of least distance then, or *apse* A, it will be as it were thrown back, since the angle S P T has been continually increasing in the progress of the planet from B to A; or, the place remaining the same, the *apse* is thrown forward as to A′, or, in other words, the *apse* progresses, or goes forward in the direction of the motion.

147. Again, soon after the planet has passed perihelion, if we suppose the deflecting force to be suddenly increased, the *direction of its motion*, which then makes an obtuse angle

with the radius vector, will be changed, so as to make an angle more nearly equal to a right angle; that is, the planet will be nearer to the apse of the disturbed orbit, and the apse still progresses. Hence, when the force drawing a planet towards the sun is increased near the perihelion position, the apse progresses; and, by similar reasoning, if the force were diminished, the apse would *regress*, or go backwards contrary to the direction of the motion.

148. Again, if the planet be near to, and approaching the aphelion B, the tendency of an increase of force will be to make the direction of motion more nearly perpendicular to the radius vector, or to bring the apse of the orbit backwards, or make it regress; and similarly, after the aphelion has been passed, the direction of motion will, by the disturbing force, make a more acute angle with the radius vector, or the apse will still *regress*. Finally, near the aphelion, if the gravitating force be diminished, the apse will progress.*

149. Since, then, a disturbing force acting towards the sun produces opposite effects at the perihelion and aphelion, there must be some intermediate points of the orbit where the effect of a slight disturbance acting towards or from the sun will be nothing; and other points where a nice determination is necessary to determine what will be the effect. At present we are only concerned with the general explanation of the phenomenon, and with the general effect on the relative orbit of the sun and earth. By the action of the planets the radial force tending to draw the earth towards the sun is sometimes increased and sometimes diminished, but the mean, or average effect, is to make the apse progress by a minute quantity amounting to about 12″ in a year.

150. This motion has been detected by comparison of the longitude of the aphelion calculated from observations of the sun at widely distant periods. The place of the perihelion or aphelion is, in fact, one of those elements of a planet's orbit which must be known before its place for an assigned epoch can be calculated. If the reader remembers the process which was sketched (in 144) for finding the longitude of the sun, he will see that the elements really involved are—

1. The mean anomaly, which depends on the mean motion, or the semi-axis major of the orbit.
2. The excentricity of the elliptic orbit.
3. The longitude of the perihelion or aphelion.

* See Airy's "Gravitation," page 41.

151. In the case of the sun, which moves in the ecliptic, these are sufficient to determine the true longitude; but, in the case of other planets, two other elements are necessary, viz.—those which define the position of the planes of their orbits with regard to the ecliptic. These are, the inclination of the plane of the orbit to the ecliptic and longitudes of the nodes—that is, of the points where the orbit cuts the ecliptic. The elements that are necessary, then, to determine the position of a body are, the mean distance, the excentricity, the longitude of aphelion or perihelion, the longitude of the node, and the inclination of the orbit to the ecliptic, and finally, the mean longitude at a given time.

152. To return, then, to the consideration of the motion of the perigee of the solar orbit. By certain assumed values of these elements, derived originally from observation, the longitudes of the sun can be calculated, and compared with longitudes derived from observed right ascensions and polar distances. Hence, the errors of the calculated longitudes can be found, and can be again expressed in terms of the errors of the elements (for it is evident that the whole error in longitude is made up of the errors produced by each of the erroneous elements taken separately); thence a series of equations can be formed from which the corrections of the elements can be obtained, and a corrected value of the longitude of the perigee or apogee can be found. Imagine this to be done for two epochs as distant as possible, that is, as distant as will allow of two sets of trustworthy observations. Two distinct values of the longitude of the perigee or apogee will thus be obtained, and the difference of these divided by the number of years, separating the observations, will give the apparent annual motion with regard to the equinox, supposed fixed. Correcting this for the precession of the equinoxes (See Chapter III.), we could obtain the real *progression of the apse* of the solar orbit, which we have said amounts to about 12″ per year.

153. Having thus treated of the theory of the solar motion, we will proceed to apply it to the explanation of the various measures of time used in civil life and by astronomers. For the purposes of common life, since our daily business is regulated by the times of the rising, setting, and culmination of the sun; since also he regulates the return of the seasons in the same recurring order; it is evident that our smaller as well as our larger measures of time, that is, our days and our years, must be regulated by this luminary. Astronomically

speaking, this method of measuring time by the sun has its defects, on account of the irregularity of his motion with regard to the equator, but still no other can be found which would so well answer all those common needs which render requisite an artificial measure; and hence astronomers have devised means of obviating the inconvenience of the irregular motion of the sun, and of still employing him for the purpose. It is not absolutely requisite that the clocks and the chronometers which are used to give ordinary indications of the lapse of time, and which *must* go on the whole regularly or equably (at least, it is manifestly impossible to make them imitate or represent any periodical inequalities of motion), should denote exactly the position of the real sun with regard to the equator. If we could always find the position of an imaginary sun moving uniformly in the equator, and on the whole never deviating far on one side or the other from the real sun, it is plain that such an imaginary body would answer almost equally well. The mornings, that is, the interval from sunrise to noon, might sometimes be a few minutes longer or shorter than the evenings, or the intervals from noon to sunset; and so we might (as we actually do) have very short afternoons before Christmas, when we should be glad of a longer duration of daylight, but this is a very slight inconvenience contrasted with the advantages of an equable standard agreeing so closely with the sun.

154. The *mean* sun, then, describes the equator with the sun's mean motion or longitude, that is, it is supposed to describe on the equator daily an arc of $59' \; 8''\cdot 33$, with a uniform motion; while the *real* sun describes the ecliptic with a motion sensibly irregular, on account of the elliptic orbit. Hence, his motion, measured along the equator, is irregular on two accounts,—first, because his place being referred to the equator by a perpendicular arc drawn to it, his distances from the equinox, measured along the ecliptic and equator, are not equal; and, secondly, on account of the unequal motion in the ecliptic. From both these causes conjoined the true sun sometimes passes the meridian before and sometimes behind the mean sun, that is, a dial which gives the true motion of the sun referred to the equator will sometimes point to twelve o'clock before and sometimes after mean noon. In fact, the real and the fictitious sun cross each other four times in the year. For example, in the year 1868, the mean noon coincided with the apparent noon, as shown by the sun's transit on April 15, June 14, August 31, and

December 24. The difference in time for any day between the transits of the real and fictitious sun is called the *equation* of time, and is given in the first page of each month in the "Nautical Almanac."

155. Astronomers are, however, in the habit of using another measure of time, viz., *sidereal* time. A *sidereal* day is the interval between the departure and the return of a star to the same meridian, as the solar day is the interval between the departure and return of the mean or the real sun. A clock used in connection with the transit instrument is set so that its index shall denote $0^h\ 0^m\ 0^s$ (or nearly so) when the first point of Aries is on the meridian, and the sidereal time commonly used by astronomers denotes the hour angle (west) of this point, and is therefore affected by the *equation of the equinoxes*. As the effect of nutation causes the motion of the equinoxes to be irregular, sidereal time is not, strictly speaking, a uniformly increasing quantity, and might be distinguished into *mean* and *apparent*, in the same manner as solar time. But the smallness of the fluctuations arising from this cause (being only $2^s{\cdot}3$ in a revolution of the moon's nodes, or 19 years) makes this refinement unnecessary, and therefore, in practice, *sidereal* noon is the instant when the true vernal equinox is on the meridian, and a sidereal day is, in practice, the interval between two successive returns of the equinox to the meridian.

156. Since the mean sun moves in the equator from west to east, contrary to the diurnal motion, with a daily motion of $59'\ 8''{\cdot}33$, or, in time, of $3^m\ 56^s{\cdot}555$, the mean solar day will be longer than the sidereal day by this quantity; and, therefore, 24^h of mean solar time are equivalent to $24^h\ 3^m\ 56^s{\cdot}555$ of sidereal time; or, the ratio of a sidereal day to a mean solar day is as

$$1 : 1 + \frac{3^m\ 56^s{\cdot}555}{24^h}, \text{ or as } 1 : 1{\cdot}002738.$$

157. We will now proceed to the explanation of the larger divisions of time. In very early ages some nations reckoned heir years by synodical periods of the moon, or the intervals between successive conjunctions with the sun. A *lunar* year with them was this interval between successive conjunctions, the time of new moon admitting of tolerably accurate observation. But the greater number of civilised nations have taken a revolution of the sun as the unit for their year, though

it required some progress in astronomical knowledge before this could be rendered an accurate standard. It is evident that the interval of time that was wanted was that in which the sun after leaving the equinox returns to it again, for on this the return of the seasons depends. This measure of time is aptly called the *tropical year*. The *sidereal year* is in like manner the time between the sun's departure from and return to a fixed star or other fixed point in the heavens. Finally, the *anomalistic year* is the interval between the departure of the sun from the perigee or apogee of his orbit till his return to it again.

158. Now, as the equinox goes backward annually to meet the sun by a quantity amounting to $50''\cdot224$, the sidereal year is longer than the tropical year in the proportion of $360^\circ : 360^\circ - 50''\cdot224$, or as $1 : 1 - \frac{50\cdot224}{1296000}$; or, nearly as

$$1 + \frac{50\cdot224}{1296000} : 1 \text{; or as } 1\cdot00003875 : 1.$$

But, according to Bessel, the tropical year (which is subject to a very slow variation) was, at the beginning of this century, equal to $365^d\ 5^h\ 48^m\ 47^s\cdot819$, the days being of course mean solar days. Hence a sidereal year is longer than this by $20^m\ 22^s\cdot9304$, or is equal to $365^d\ 6^h\ 9^m\ 10^s\cdot749$. This result the reader may verify for himself.

159. Again, the sidereal year is shorter than the anomalistic year in the proportion of $1 : 1 + \frac{12}{1296000}$; or of $1 : 1\cdot00000926$, and the reader may readily calculate its length.

160. We have not much space to devote to the consideration of the formation of the *calendar*, or the means taken to prevent the accumulation of error in the course of years on account of the hours, minutes, and seconds, which, over and above the 365 days, make up the tropical year; but we can give a few words of explanation. If we were to assume the year to consist of 365 days instead of its exact amount, an error amounting to very nearly a day would be entailed every four years, and this in a century would throw the minor divisions very nearly a month out with regard to the seasons. It was, in fact, this accumulated error, amounting at the time to ninety days, which led to the Julian correction, so called because of its celebrated author, Julius

Cæsar, who carried it into effect about forty-five years before the Christian era, with the assistance of the Egyptian astronomer Sosigenes. This correction consists in intercalating, or adding, a day in February every fourth year; that is, making every fourth year to consist of 366 days instead of 365 days, and the corresponding February to consist of twenty-nine days instead of twenty-eight days. The year thus augmented was called by the Romans *bissextile*, and is now here familiarly called leap-year. But it is evident that even now the correction is imperfect. It is based on the supposition that the average year consists of 365 days 6 hours, which exceeds its true amount by 11 minutes 12 seconds. The correction is therefore too great by nearly $\frac{11\cdot2}{360}$, or by $\frac{1}{32}$ part nearly. Hence arose the Gregorian correction devised by Pope Gregory XIII., in the year 1582, which was adopted in Catholic countries in the sixteenth century, but not in England till the year 1752, when the calendar, which was wrong by 11 days, was corrected, and the New Style commenced.

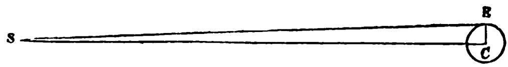
161. The Gregorian correction consists in omitting three leap-years out of one hundred; that is, in omitting one leap-year at the beginning of three successive centuries, and retaining it at the commencement of the fourth, and is equivalent to subtracting $\frac{3}{100}$ part from the Julian correction to the year. Now we saw that the quantity really wanted is $\frac{1}{32}$ part, and the difference is so small that it will not cause an error of a day in four thousand years. The leap-years are those which can be divided by four without remainder (thus 1868 was a leap-year), and the remainder after dividing any other year by four will indicate the number of years since the last leap-year. The Gregorian correction omits the intercalation of the day in the secular years 1700, 1800, 1900, but retains it for the next secular year, 2000, and so on, repeating the omission of the intercalation every fourth century: and the rule for determining which of the years commencing centuries are bissextile and which are not, is analogous to the former; omitting the last two ciphers, if the remaining number is divisible by four the year *is* bissextile, but if it be not so divisible the year *is not* bissextile.*

162. We have now concluded our remarks on the theory of the apparent motion of the sun, and its application to the

* For a very valuable article on the Calendar and the Theory of Chronological Epochs, see Sir J. Herschel's "Outlines of Astronomy," part iv. chap. xviii.

measure of time, and it remains that we give a short account of what is known of the physical constitution of this wonderful body, and its relation to us with regard to our comfort and convenience.

163. Our attention is first drawn to its size and mass; and the principles already explained will enable the reader to see that we can directly measure these elements. The solar parallax has been accurately measured, and according to recent investigations amounts to about 8″·85. This, the reader will remember, represents the angle which the semi-diameter of the earth would subtend at the centre of the sun, and from this the distance is easily deduced.



Thus, in the above figure, if s be the centre of the sun, and c that of the earth, c E the earth's equatorial semi-diameter,

$$\text{Then,} \quad \text{s c} = \text{E c} \times \text{cotan. E s c.}$$
$$= \text{E c} \times \text{cotan. } 8''{\cdot}85.$$

By calculation, the distance s c will be found to be 23,316 times the length of the earth's semi-diameter, or, in round numbers, to above 92,400,000, miles. Now the mean value of the sun's angular diameter, as seen from the earth, is, according to Bessel, 32′ 1″·8. Hence it is evident that the diameter, expressed in miles, will be 184,800,000 × tan. 16′ 0″·9, that is, to twice the distance multiplied by the angular semi-diameter. This gives for the actual diameter of this stupendous globe, expressed in English miles, the almost incredible value of 860,000 miles. It will perhaps assist the reader in forming an idea of the real size of the diameter of the sun, thus set down in figures, if we compare it with the dimensions of the lunar orbit. The mean distance of the moon is about 240,000 miles. If then, we imagine the centre of the earth to coincide with that of the sun, the surface of the latter body would not only include the lunar orbit, but would extend almost as far beyond. The mass of this body is no less wonderful (our readers who have read the Rudimentary Treatise on Mechanics will be familiar with the astronomical meaning of the term *mass*). Since all bodies in nature gravitate towards each other, the energy or force with which one body of the solar system attracts or draws any other is represented by this term, and if the

matter of which the attracting body is composed be homogeneous, the mass would be proportioned to the quantity of matter, though this latter idea belongs more to bodies of small size, which we have occasion to compare on the surface of our own planet. However, in astronomy, the attracting force only of a planet on another is meant by the term, and this is measured, as we have had occasion to explain (133), by the space through which the attracted body is deflected in a given time, or by the curvature of its orbit. On this depends the time of revolution of the planet, and conversely the known times of revolution of planets which have satellites, compared with the times of revolution of the satellites round their primaries, are used for determining the mass of the sun. Thus if M, m, and m' be the masses of the sun, the earth, and the moon, and A and a the semi-axes of the solar and lunar orbits, then if T and t represent the times of revolution of the earth round the sun and of the moon round the earth, that is a sidereal period of each of these luminaries; we shall have (140)

$$T^2 = \frac{4\,\pi^2\,A^3}{M + m}, \text{ and } t^2 = \frac{4\,\pi^2\,a^3}{m + m'}.$$

Hence, $$\frac{M + m}{m + m'} = \frac{A^3}{a^3} \cdot \frac{t^2}{T^2}.$$

Now, the radii of the lunar and solar orbits are in the proportion of 240,000 : 92,400,000, or as 1 : 385; and the revolution of the moon round the earth is to that of the earth round the sun in the proportion of 1 : 13·4 nearly.

Hence, $$\frac{M + m}{m + m'} = \frac{(385)^3}{(13{\cdot}4)^2} = 317{,}810 \text{ nearly.}$$

And as m is so small compared with M, we may safely neglect it in making this comparison.

Therefore, $$M = 317{,}810 \times (m + m')$$

that is, the mass of the sun is approximately three hundred and eighteen thousand times the sum of the masses of the earth and moon.

164. To form some idea of the effect of this enormous disproportion of masses, let us assume that $M = 318{,}000 \times m$, the mass of the moon being small, and try what will be the proportion of the pressure exerted on two individuals, one on the surface of the sun, and the other on that of the earth.

The effects of the masses will be the same as if the same energies were exerted at the centres of the sun and earth, and will be inversely proportioned to the squares of the distances from the centres to the surfaces, that is, to the squares of the semi-diameters. Let R and r be the semi-diameters of the sun and earth, P and p the pressures exerted on the same particle of matter at the surfaces,

Then, $$P = \frac{M}{R^2}, \text{ and } p = \frac{m}{r^2}.$$

Hence, $$\frac{P}{p} = \frac{M}{m} \times \frac{r^2}{R^2}$$

$$= 318{,}000 \times \frac{(4000)^2}{(430{,}450)^2}$$

$$= \frac{318{,}000}{(108)^2} \text{ nearly}$$

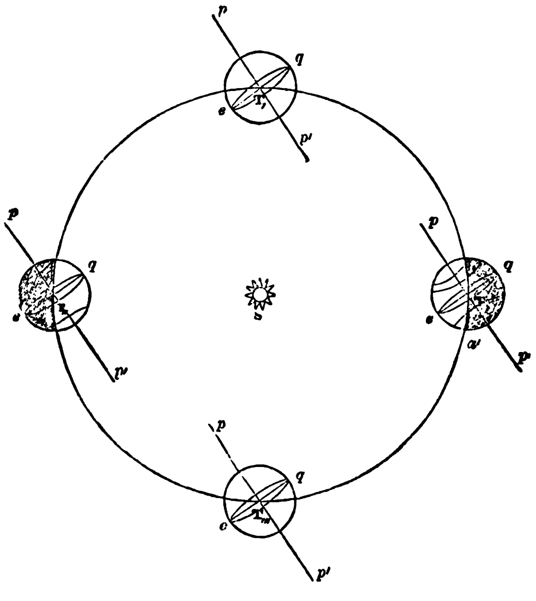
$$= 27\tfrac{1}{2} \text{ nearly.}$$

Hence a man weighing 150 lbs. at the earth's surface, would be, at the surface of the sun, pressed towards the centre with a force equivalent to $27\frac{1}{2} \times 150$ lbs., or to nearly two tons. In fact, he would be completely crushed by his own weight or gravitating tendency. The same reasoning will apply to some of the planets which have satellites, and the result is that there is no known planet but the earth, which is adapted for the muscular energy and temperament of man and the other animals, and hence we have a beautiful specimen of design and of the adaptation of the globe which we inhabit to the nature and constitution of its inhabitants.

165. The vicissitudes of the seasons are regulated by the elevation or depression of the sun in his annual circuit above or below the equator. Thus at midsummer his elevation above the equator is about $23\frac{1}{2}°$, being equal to the obliquity, or inclination of the ecliptic to the equator. At midwinter he is depressed below the equator by the same quantity. Finally, at the vernal and autumnal equinoxes he is situated in the equator, being then at the points of intersection of the equator and ecliptic.

166. We will show by a diagram the effects produced on the length of the day and night by these circumstances. Let T, $T_{\prime}$, $T_{\prime\prime}$, $T_{\prime\prime\prime}$, represent four positions of the earth, corresponding to the summer solstice, the autumnal equinox, the winter solstice, and the vernal equinox, in its annual orbit

round the sun, S; let *p p′* be the axis of rotation continuing always parallel to itself, and let *e q* be the equator. Then at T the sun is above the equator by the angle S T *e*, or by the obliquity (23½°), and if we draw *a a′* perpendicular to S T, the shaded portion of the globe represents the part on which the sun's light cannot fall, or where night exists, and the unshaded portion represents the illuminated hemisphere,



or the portion where day prevails. Hence by drawing small circles parallel to the equator, we observe that for all parts above *a*, that is, in the northern arctic regions, there is no night, and that for all parts below *a′*, that is, for the southern arctic regions, there is no day;—for any point above the equator, the days are longer than the nights by the greatest possible quantity;—and for any place in the southern hemisphere the nights are longer than the days by the greatest possible quantity. All these phenomena will evidently be reversed at T$_{\prime\prime}$, or the winter solstice, where the north pole is turned away from the sun, and the south pole turned towards him. Finally, at T$_{\prime}$ and T$_{\prime\prime\prime}$, or at the equinoxes,

the days and nights are equal throughout the globe, since the half of any circle of latitude is half in light and half in darkness.

167. With regard to the physical peculiarities of the surface of the sun, our knowledge is derived from telescopic observations. If the image of the disk be projected on a screen in a darkened chamber, or if it be viewed directly through a telescope of which the eye-piece is provided with coloured glasses for the protection of the eye, it will be generally found that the disk is not uniformly bright, and that in some places spots (*maculæ*) of absolute darkness occur upon it. These spots vary exceedingly at different times. At some periods large groups of these spots suddenly break out and continue for a considerable time, while at other times the disk is comparatively clear for a long period. They are exceedingly irregular in their form, but they all, when of any magnitude, agree in having the middle portion of intense blackness, while the margin is surrounded by a penumbra only partially shaded. If the attention be directed from day to day to any remarkable spot which has appeared near the sun's eastern borders, and its position be mapped down on a circle drawn on paper, it will be found to have a motion in an elliptic curve from east to west, increasing in rapidity as it approaches towards the centre, and becoming very slow near the western border. From such observations it becomes evident that the spots are not bodies revolving round the sun, but that they exist upon his surface and revolve with him. They can frequently be observed during at least one or two revolutions, and in rare instances they have been watched during several; but small ones frequently disappear in the course of a few days. Advantage has been taken of the durations of these revolutions for the determination of the time of rotation of the sun. The problem is difficult and not adapted for a popular treatise; and the reader may be referred to Sir J. Herschel's "Outlines of Astronomy" for an excellent sketch of the method by which the time of rotation is deduced. We will content ourselves with simply recording the results. According to the best recorded determinations, the inclination of the sun's equator to the ecliptic is about 7° 20′, the longitude of the ascending node being 80° 21′, and the period of rotation is $25^d\ 7^h\ 48^m$.

The spots are generally confined to the neighbourhood of the sun's equator, and are never found in the polar regions; they are also frequently found arranged in the manner of

belts parallel to the equator. These circumstances seem to indicate that they owe their origin to the rotation, and are produced by disturbances in the solar atmosphere occurring much in the same way as storms above the surface of our own planet. Sir William Herschel's hypothesis concerning their formation, which is based on these circumstances, is the following. He supposes "luminous strata of the atmosphere to be sustained far above the level of the solid body by a transparent elastic medium, carrying on its upper surface (or rather at some considerably lower level within its depth) a cloudy stratum, which, being strongly illuminated from above, reflects a considerable portion of the light to our eyes, and forms a penumbra, while the solid body shaded by clouds reflects none. The temporary removal of both the strata, but more of the upper than the lower, he supposes effected by powerful upward currents of the atmosphere, perhaps from spiracles in the body, or from local agitations." *

168. In connection with the *maculæ*, or spots, another singular phenomenon is witnessed on the surface of the sun, which consists in strongly-marked curved or branching streaks or lines, brighter than the surface in the neighbourhood, called *faculæ*. They are most commonly seen near the borders of the disk, and are either in the neighbourhood of large spots or are precursors of their formation. They bear every appearance of owing their origin to violent agitations in the luminous atmosphere or envelope of the sun.

169. Some additional and most interesting knowledge of the constitution of the solar atmosphere has been gained by the observations of total eclipses of the sun, and especially by the well-organised series of observations which were made along the line of totality of the eclipses of 1851, July 28; of 1860, July 18; and of 1868, August 17-18.

The eclipse of 1851 was total for several countries in the North of Europe, and especially for Sweden, Norway, and parts of Prussia and Poland. Parties of observers, well furnished with instruments and with elaborate instructions for the observation of every phenomenon which former experience had suggested, were despatched from England, France, and Germany, to the various towns and stations (previously selected) which could insure the full observation of the phenomena in all possible phases. The circumstances were

* Sir J. Herschel's "Outlines," page 229.

exceedingly favourable, the moon being near perigee, and the eclipse occurring early in the afternoon, when the sun was high.

The results fully answered the expectations which were formed concerning it. All the observers agree in the main features of this grand and striking phenomenon, while the variations, arising from their differences of locality, give much important information concerning some circumstances which could not have been obtained at any one station. As soon as the disk of the sun was completely hidden by the moon, a bright corona of white light, similar to that of an aureola or glory, was seen round the border of the moon, now appearing like an intensely black patch in the sky. Round the black circle of the moon, at irregular distances, were seen bright and mountainous, or rather flame-like, protuberances. The greater number of these, according to the accounts collected from the different observers, seemed to be in contact with the moon's limb, and were broader at the bottom than at the top, but one at least was seen distinctly separated, and suspended, as it were, in the atmosphere surrounding the sun. In one direction, many observers agree in noting a large red *sierra*, or long mountainous-looking range, with an irregular tooth-like edge. Another protuberance had the shape of a sickle with the top broken off, and with another irregular-looking mass very near it, but neither in contact with it nor the moon's edge. Such prominences as were near that part of the sun's limb towards which the moon was moving, were observed to decrease in height (the moon passing over them), while those on the opposite part of the limb increased in height. It is evident, therefore, that these wonderful phenomena belong to the sun and not to the moon, and it is probable that they are of the nature of illuminated clouds suspended in the atmosphere surrounding the luminous envelope. There is little doubt also that the luminous ring or corona belongs to the sun and not to the moon, though its boundaries are so vague (the light becoming gradually weaker as the rays recede from the centre) that it was impossible in general to determine whether it was concentric with the sun or with the moon.* (See Vignette.)

The interest which was excited by the observations of the eclipse of 1851 induced astronomers to look eagerly

* See *Notice of the Royal Astronomical Society* for January 9, 1852, for the collected accounts of observations.

for the next great eclipse which would be visible in Europe, namely, that of 1860. Its central line passed across Spain, and the British Government put at the disposal of the Astronomer Royal, and other astronomers who intended to observe it, the large steamer *Hilamaya.* At some of the important stations, as at those chosen by the Astronomer Royal and Mr. (now Dr.) De la Rue, the circumstances of weather were favourable, and excellent physical observations were made, confirmatory of those made during the eclipse of 1851. In particular, it was proved beyond a doubt that the red prominences belonged to the limb of the sun, and not to that of the moon. Mr. De la Rue succeeded in his attempts at photographing the various phases of the eclipse to such an extent, that several minute particulars were found registered in the photographs which would have otherwise escaped, and measures were afterwards made from them of the distances of the cusps and limbs, rivalling in accuracy the most refined micrometrical measures. Mr. De la Rue's detailed account of the eclipse formed the Bakerian Lecture of the Royal Society for the year 1862, and will be found in the *Philosophical Transactions* for that year. Another excellent account is that by the late Dr. Bruhns, of Leipzig, in the *Astronomische Nachrichten*, No. 1292.

The total eclipse of August 17-18, 1868, was central over a great part of India and some of the islands of the Indian Ocean, and was of very great importance, on account of the time of totality for stations on the central line being almost the greatest possible. Amongst the expeditions which were organized for observing it, two were sent from England, under the auspices of the Royal Society, and the Royal Astronomical Society respectively, the former being directed by Major (then Lieut.) Herschel, who went to Jamkandi, and the latter by Colonel (then Major) Tennant, who observed at Guntoor. A German expedition selected for its station a position near Aden on the Red Sea; this included Drs. Weiss, Oppolzer, and Tiele. Two French expeditions were also sent out, of which one was under the charge of M. Stéphan, the astronomer at Marseilles, who observed at Whatonne, on the Malaccan peninsula; and the other under that of M. Janssen, who observed at Guntoor. Important discoveries were made by means of the spectroscope, concerning the nature of the red prominences seen in every total eclipse round the borders of the sun. A short account of spectrum analysis will be given in an appendix to this volume, and it

may be sufficient here to state that the observations made during the eclipse prove that the red prominences consist of incandescent gases; but much yet remains to be learnt with regard to their exact nature. Another remarkable discovery has been made almost simultaneously by Mr. Lockyer and M. Janssen, namely, that it is practicable to obtain spectra of the red prominences at all times when the sun is visible, and not only during a solar eclipse. A total eclipse which occurred on August 7th, 1869, was well observed by several parties in the United States; and one which was total on December 22nd, 1870, in Spain, Sicily, and North Africa, was watched by several parties, both European and American, though the weather was unfortunately bad at several of the stations. We have only space to mention later total eclipses; that of 1871 in India, of 1875 in Siam, and of 1878 in the United States. Important extensions of our knowledge have been made at all, especially with regard to the nature of the so-called corona, which have thrown much new light upon the subject of solar physics. (See page 171 in the Appendix.)

170. The last phenomenon which we have to notice in connection with the sun is the *zodiacal light*. If we look at the western part of the sky on a fine spring evening after the setting of the sun, we observe a brightness which we feel at first tempted to attribute to the still lingering twilight, except that it is considerably more intense; but, if we continue to watch this bright part of the sky till the sun has gone down so far as to prevent any of his rays from being reflected or refracted by our atmosphere, or till all effect of twilight has disappeared, the light still remains, and its intensity may be judged of by comparing the western with the eastern sky. The one exhibits a fine straw-coloured glow of light, fading away and becoming lost about forty or fifty degrees from the horizon; the other exhibits the dark blue which is characteristic of the sky during a fine winter night. This light is broadest at the horizon, and tapers away gradually till it is finally lost in a point nearly in the direction of the ecliptic. Indeed, if it be accurately observed, it will be found to have the ecliptic nearly for the axis of its lenticular or conical figure, and will be seen, if Venus be in the sky, to extend beyond her. It is very faint in this climate, and it is very difficult to determine the exact limit at which it terminates; and though it evidently attends the sun—being always observed in the direction of the ecliptic or sun's path, preceding him in the morning, before sunrise, in the autumn

months, and lingering behind him, and lengthening our twilight, in the spring, after he has set in the evening—yet philosophers have not been able to form any satisfactory theory concerning it. It is one of those wonders of the heavens which, for the present, we must be content with admiring, in the hope that the progress of science will, at some future time, throw clearer light upon its cause and formation, and afford fresh occasion for adoring in His works the great Architect of the universe, who by His word made and placed in this wonderful order all the orbs of heaven, whose motions it is the highest praise of man's intellect partially to understand and explain.

171. From the action of the rays of this great body, the sun, arise all the motions that are discovered on the surface of our planet. To the disturbances in our atmosphere, produced by the unequal action of the heat coming from him, we owe the breeze that refreshes us in summer, and the storm that drives away infection from our dwellings. By his agency water retains its liquid properties, and the rains which he has forced from the clouds descend to the sea, again to be raised in vapour for the renewal of the same fertilising process. His action forces the sap into the vessels of trees, shrubs, and vegetables, and covers the earth with verdure and plenty. Owing to his more oblique position in winter, his action is then partially suspended: the rivers become congealed and the moisture of the ground is converted into ice; snow covers our fields, and protects while it covers them. The action of the teeming earth is for a time usefully suspended to gather fresh strength for the coming season, when the sun's increasing warmth shall renew the energies of vegetation, and the trees shall again put forth their buds and their leaves: Nature then bursts forth again, as if refreshed with her long wintry sleep, and the marvellous economy of agricultural processes is renewed for the benefit of mankind

CHAPTER V.

THE MOON.

172. NEXT to the Sun, the celestial body most interesting to us is the Moon. Independently of its use in regulating our minor divisions of time—that is, by the divisions of the year into months—it is of incalculable use in nautical science, and its motions afford the only means for the accurate determination of the place of a ship on the ocean, or for measuring the terrestrial longitude reckoned from a fixed point of departure. The proximity of this secondary planet is another interesting feature in all our discussions concerning her. By means of observations made with good telescopes, the part of her surface turned towards us has been mapped with almost the same accuracy as that of the earth; every prominent or conspicuous point is laid down in the lunar charts with the same fidelity with which our own mountains, and seas, and rivers have been depicted; the heights of her mountains have been measured, and the physical peculiarities of her surface are now tolerably well known.

173. On all these accounts the knowledge of the motions of our satellite becomes an object not only of very great interest, but of absolute necessity. The theoretical astronomer speculates upon the peculiarities of her orbit for the advancement of abstract science, but the great practical benefit from his labours is obtained by the merchant and the sailor in the safety of precious cargoes and still more precious lives; for in the long voyages of modern navigation by which are exchanged the commodities and intelligence of far distant countries separated by thousands of miles of ocean, the long previously predicted and published places of the Moon amongst the stars are frequently found of inestimable service.

174. We arrive at a knowledge of the chief elements of

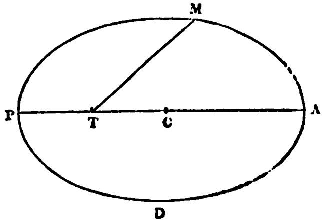
the lunar orbit in the same manner as for that of the sun, that is, by observations carried on from day to day. The most careless observer cannot but take notice that her place in the heavens varies rapidly from one day to another; that she has in fact a daily motion from west to east, or in opposition to her diurnal rotation, of about three-quarters of an hour—that is, that her time of arriving at the meridian is on the average retarded daily by that quantity. By simply mapping out her path in the heavens on a globe by means of the known stars that happen to be near her, from night to night, it would be easy to see that the apparent path in the heavens is nearly a great circle of the sphere, and that this great circle makes a small angle with the ecliptic. If, indeed, we were to apply the corrections to her observed right ascensions and declinations which are due to refraction, parallax, &c., according to the principles explained in Chapter III., we should find that her path was (accurately enough for one revolution) a great circle inclined at an angle of very nearly 28° to the equator, or of 5° to the ecliptic.

175. By observations also made near the time of her crossing the ecliptic, where her latitude is nothing, the calculated longitudes and latitudes will afford means, by simple proportion, of determining the longitude of the point where she crosses the ecliptic, that is, the longitude of her *node*. If also observations be continued through several revolutions, and the longitude of the node be thus determined, it will be found that this point is not fixed, but has a *backward* motion along the ecliptic, similar in its character to the *precession* of the equinoxes, but incomparably more rapid. In fact, observations continued throughout the space of several years show that the *nodes* regress through the whole circle, or come back to the same point of the ecliptic, or perform a revolution, in the space of rather less than nineteen years.

176. Again, when we inquire into the nature of the curve which she describes round the earth in the plane of her orbit, observations of a similar character to those detailed in our chapter on the solar motion will show us that her orbit is on the whole elliptical, thus obeying Kepler's First Law; and a comparison of her velocity (measured by her daily change of longitude), when at her greatest and least distances (determined by her apparent diameters measured at those times), will show us that Kepler's Second Law of elliptic

motion is also obeyed: viz., *that the areas swept out by the radii vectores are proportional to the times.*

177. A comparison also of the greatest and least diameters will show that the excentricity of the ellipse is about 0·0635. Thus, if P and A be the *perigee* and *apogee* of the orbit round the earth T (that is, the points of least and greatest distance), C the centre of the ellipse, then TC is the excentricity, supposing AC, the mean distance, to be unity. Let D_1 and D_2 be the observed diameters at P and at A:



Then, $\frac{PT}{AT} = \frac{D_2}{D_1}$; or, $\frac{1-e}{1+e} = \frac{D_2}{D_1}$; whence, $e = \frac{D_1 - D_2}{D_1 + D_2}$.

If $D_1 = 33' \, 30''$, and $D_2 = 29' \, 30''$, which are nearly the limiting observed values of the diameter, $e = \frac{4}{63} = 0{\cdot}0635$, agreeing with the value given above.

178. Now, if the longitudes of the perigee and apogee of the orbit be observed, by means of the knowledge gained by the variations of the diameter, or, which is better still, by the variations of her velocity or daily increase of longitude, it will be found (as was the case in the solar orbit) that these points are not fixed, but have a direct motion, that is, in the direction corresponding to increase of longitude, so rapid as to carry them round the whole circle in about nine years. This revolution of the perigee, like that of the node, is not uniform, that is, it is sometimes quicker and sometimes slower than its mean value, and sometimes even regressive; and it has a *secular* variation, that is, its mean motion, derived by observations made at two distant epochs, would not agree with the mean motion determined by observations made at other two distant epochs. But at the beginning of the present century, the motion was such that the time of a tropical revolution of the perigee was 3231·475 days.

179. There is still one more peculiarity of the motion of the moon to be taken notice of, viz., the *acceleration of the mean motion.* For example, if the moon's place be computed without regard to the acceleration, for the epoch of an ancient eclipse, such as the Babylonian eclipses transmitted to us

by Ptolemy, which were made several centuries before the Christian era, we find the longitude thus computed to differ by nearly a degree and a half from the longitude computed by the conditions of the eclipse, that is, by the known relative positions of the sun and moon. The moon's place, computed by the eclipse, is in fact in all such cases greater than that computed from the tables; that is, the tables have thrown the moon's place too far back, or too great a mean motion has been allowed. This *acceleration of the mean motion of the moon* was first discovered as a fact of observation by Halley, and its physical cause was afterwards deduced from the theory of gravitation by Laplace, and was shown to depend on the secular diminution of the excentricity of the earth's orbit. It is a very remarkable example of that class of equations or corrections of long period, known by the name of *secular equations*. Though it has existed since the earliest ages of astronomical observation, still it is *periodical* and not *permanent;* that is, after a great number of ages it will be reduced to nothing, and after that the motion, instead of being *accelerated*, will be *retarded*, through an equally long period. If the fact were otherwise, the moon must, in however remote a period, be drawn in towards the earth with a still accelerated motion, and would at length be attracted to and fall on its surface. The motion of the node and that of the perigee are also both subject to *secular equations*.

180. The above remarks will serve to show how the motion of the plane of the lunar orbit and the motion of the moon in that plane have been observed. By refined processes depending on such observations, the value of each of the foregoing elements has been obtained with very great accuracy. Thus, for the beginning of the present century (1801), the longitude of the ascending node was 13° 53′ 22″, and its time of revolution round the ecliptic was 6798 days, or about eighteen years and six months; while the time of a *synodic revolution*, that is, the interval between two successive meetings with the sun, was 346·62 days, the node having gone backwards on the ecliptic to meet the sun through an arc of 19° 20′, nearly. The mean inclination of the lunar orbit to the ecliptic is about 5° 8′ 48″, and it varies from about 5° to 5° 17′. The direct motion of the perigee for the beginning of the century was, as has been said before, such as to complete a *tropical revolution* (that is, setting out from the equinox and returning to it again) in 3231·475 days.

181. The time of revolution of the moon in her orbit may,

as in the case of the sun, be distinguished into *tropical*, *sidereal*, and *anomalistic*. The time of a *tropical* revolution is the interval between the departure of the moon from the equinox till its return to it. The time of a *sidereal* revolution is the interval between the departure from and return to the same point of the heavens. And an *anomalistic* revolution comprises the time between the departure from perigee or apogee till the return to it. In addition, for the moon we have a *synodic* revolution, that is, the interval between the departure from and return to conjunction with the sun, which depends on the relative motions of the two bodies. We have not space in so brief a treatise to repeat the reasoning by which these values are derived from the tropical period by means of the elements given above. It is sufficient here to give the values, leaving the student to exercise himself by deducing them one from the other.

182. By very exact observations of the mean motion of the moon with regard to the equinox made at the interval of a century, it is found that the value is 13° 10′ 35″; hence the time of describing 360°, or that of a tropical revolution, is $27^d\ 7^h\ 43^m\ 4^s.7$.

183. From this can be deduced, by means of the values of the sun's mean motion, the annual precession, and the motions of the lunar node and apogee, the following values:—

		d.	h.	m.	s.
Time of Synodic revolution	=	29	12	44	2·8
" Sidereal revolution	=	27	7	43	11·6
" Anomalistic revolution	=	27	13	18	37·4
" Draconic revolution, or revolution with relation to the node	=	27	5	5	35·6

184. Thus far we have considered the moon to move in an elliptic orbit which may be considered to be described in a plane having a *direct* motion of revolution round an axis passing through the earth's centre, while its point of intersection with the ecliptic retrogrades, and its inclination to that plane has periodical changes. But this supposition is only approximately true. The moon does not move truly in such an ellipse, and it is only for convenience, or for the greater facility of calculation of her true place, that she is supposed to do so. If, for example, we were to take the elliptic elements for a given epoch, and, by the known value of the excentricity, construct, as in the case of the solar orbit, a table of the values of the equation of the centre, this

quantity added to her mean anomaly would not give her true place in the heavens for any given time, after making every allowance for the retrogradation of the node, the variation of the inclination of the orbit, and the progression of the apogee. In fact, we should find, by a very simple comparison of calculated and observed places, that the calculated place was sometimes considerably in advance of, and sometimes behind, the observed place.

185. The first and largest of the inequalities thus discoverable by observation is called the *evection*, and was discovered by Ptolemy, having escaped the observation of his celebrated predecessor, Hipparchus. In fact, Hipparchus, whose observations of the moon were made only at conjunction and opposition, had no opportunity of recognising the evection, because at those times it became confounded or mixed up with the equation of the centre, and simply showed too small a value of this equation, or of the excentricity of the orbit. Ptolemy, however, who observed the moon at *quadratures*, that is, at 90° distance from the *syzygies* or conjunctions and oppositions, discovered the true law of the inequality, which has for its argument twice the difference of the longitudes of the moon and sun, *minus* the moon's mean anomaly, and varies as the sine of this quantity. Its greatest value, or the *co-efficient* of the preceding argument, is about 1° 20′ 29″·5.

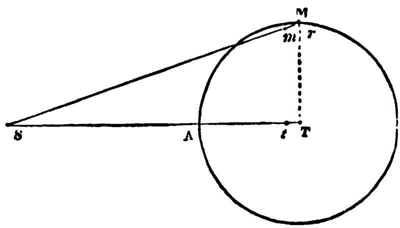
186. The physical cause of the *evection*, and indeed of almost all the inequalities of the moon, except the equation of the centre, is the disturbance produced by the sun's action on the relative orbit of the earth and moon, and of this we will attempt a brief explanation. It admits of easy proof from observation that this inequality depends on the position of the line of apsides, that is, of the major axis of the lunar orbit; for, if this line be *in syzygy*, that is, coincident with the line joining the sun and earth, the moon, after moving from apogee through a quarter of her orbit, that is, to quadratures, will be found *behind* the place computed from the equation of the centre by more than a degree, but if the line of apsides be in quadrature, her true place, some days after quitting the apogee, will be found to be *before* the computed place by nearly the same quantity. Imagine now the line of apsides to be in syzygy; then, since the moon moving from apogee has been found behind her computed place, too small a correction has been subtracted *for the equation* of the centre, or the equation of the centre

is apparently increased, denoting an increase of excentricity. If, on the contrary, the line of apsides be in quadrature, the equation of the centre, and the excentricity, would appear to be diminished. Hence the observed effect of the evection is to increase the excentricity of the orbit when the apsides are in syzygy, and to diminish it when they are in quadrature.

187. Let us now consider whether the action of the sun in disturbing the lunar orbit will give an adequate explanation of this and other observed inequalities. For simplicity, we will first suppose the undisturbed orbit to be circular, and trace out some of the consequences of the disturbing force on this supposition, leaving the evection to the last, because it depends upon the excentricity of the orbit, and, though the largest of the inequalities, and coming first as a fact of observation, does not admit of so easy a popular explanation. It must be remembered that the effect of the sun in disturbing the moon depends on the *difference* of his actions upon the earth and the moon. The sun tends to draw both bodies towards his centre, and if they were at equal distances from him, and moving in parallel directions with equal velocities, it would draw them through equal spaces in equal times, and their relative orbits would not be disturbed. But none of these conditions generally hold; the direction of the motion of the moon, her velocity, and her distance from the sun, are perpetually varying during her revolution round the earth, whilst, for one revolution, these quantities may be considered for the earth pretty nearly constant; hence disturbances arise in the orbit, and it is plain that the points of syzygy will be those at which she is particularly affected, since at conjunction she is nearest to him, and at opposition farthest from him. If she be nearest to him, or at conjunction, then she is pulled towards him more than the earth is, and, her gravitation to the earth being lessened, the curvature of her orbit is lessened; if, on the contrary, she be farthest from him, she is pulled less towards him than the earth, and the curvature of her orbit is also lessened. In both these cases the disturbing force is directed *from* the earth in the direction of the radius vector. But at any intermediate point, the disturbance in the direction of the radius vector will not be the only one, since the sun does not draw the moon in the direction of that line. In all cases, however (neglecting the inclination of the orbit to the ecliptic), the disturbance can *be always resolved*, by the ordinary laws of mechanics, in

two, one of which is in the direction of the radius vector, and the other at right angles to it, or approximately in the direction of a tangent to her motion, her orbit being nearly circular. These forces are called respectively the *radial* and the *tangential* disturbing force; the first increasing or diminishing the moon's gravitation to the earth, the latter increasing or diminishing her velocity in her orbit.

188. If we were again to take the case for which the moon is in quadratures, and her distance from the sun nearly equal to the earth's distance from the sun, then the sun will pull them equally, but not in the same direction. Thus let S, T, and M be the positions of the sun, earth, and moon (near quadrature), when S T = S M. Then if, in a given time, the sun pull the earth and moon in equal times through the spaces M *m* and T *t*, these spaces will ultimately represent the forces exerted upon each. Now M *m* may be resolved into M *r*, in the direction of T M and *m r*, parallel to T *t*. Hence, in this case, T *t* and *m r* (= M *m*), being equal, the effective disturbing force is represented by M *r*, in the direction of the radius vector. Hence at quadratures, as well as at syzygies, the disturbing force is in the direction of the radius vector, but at quadratures it is directed *towards* the earth, and is much less than at syzygies. At any intermediate part of the orbit the force will be partly *radial* and partly *tangential*, and the effects of these respectively in increasing or diminishing the gravitation to the earth, and in increasing or diminishing the velocity in the orbit, can be traced out for any assigned position of the orbit by similar resolution of the disturbing force. We may see, however, immediately, that since at M the radial force is directed towards T, and at A it is directed from T, there is some intermediate point where it vanishes, and where the whole disturbing force is tangential, and similarly for the other three quadrants. With respect also to the tangential force, it may be shown that it accelerates the motion of the body from quadrature to syzygy, but it retards it from syzygy to quadrature.



The above considerations will tend to show the general

effects of the sun's disturbing force upon the orbit which the moon would describe in a revolution, if it be supposed circular; and in particular, it will serve to show the nature of one of the lunar inequalities, called the *variation*, which depends upon the oval shape of the orbit, and on the action of the tangential force, and causes the angular motion of the moon to be greater than the mean at syzygies, and less than the mean at quadratures, and therefore causes the moon to be before her mean place from syzygy to quadrature, and behind it from quadrature to syzygy.

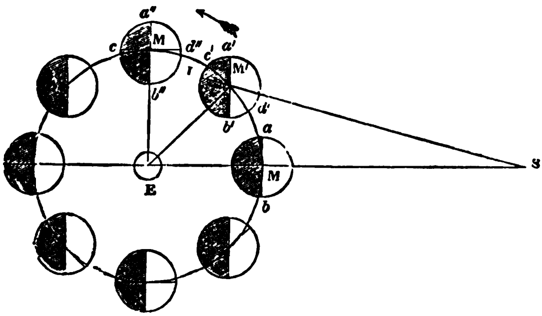
189. Thus far we have proceeded on the supposition that the moon's undisturbed orbit is circular, or has no excentricity. The introduction of the consideration of the excentricity does not greatly concern the moon's variation, but it is immediately concerned in the explanation of the greatest of the *inequalities*, viz., the *evection*, which we proposed to explain. The reader will, for the present, take for granted, without further explanation than that offered in the discussion of the solar orbit, that by the action of the disturbing forces, the major axis of the excentric orbit, that is, the line of apsides, is made to revolve with a direct motion; that is, that the perigee progresses with, on the whole, a rapid yet very irregular motion. As the relative positions of the earth and moon are very much affected by this circumstance, it is evident that the effect of the disturbing forces in producing inequalities will also be much affected by the position of the line of apsides. The principal effects may be thus described, though we must refer the reader to larger works for a complete explanation. If the lines of apsides be either in syzygy or in quadrature, though, during a revolution of the moon, the excentricity is alternately increased or diminished, yet, on the whole, the excentricity is neither increased nor diminished. If, however, the line of apsides be inclined in such a manner that the moon passes the apsides (perigee or apogee) before passing the line of syzygies, the excentricity is diminished at every revolution of the moon. If, finally, the position of the line of apsides be transverse to the former, so that the moon passes it after passing the line of syzygies, the excentricity is increased in every revolution of the moon. As, then, the earth in its real orbit, or the sun in its apparent orbit, is carried round in its annual circuit, the line joining them is brought into every position with respect to the line of apsides of the lunar orbit, and the excentricity will be either increas-

exactly filled with light; she is then distant from the sun by about six hours of Right Ascension, and is said to be *dichotomised*. She then becomes *gibbous*, or is more than half illuminated, and after separating from the sun by twelve hours of Right Ascension, has the whole disk illuminated, or is at the full. After this, she wanes, or the illuminated portion of the disk (still turned towards the sun, and therefore, with regard to the east and west points of the horizon, illuminated on the side opposite to that of the increasing moon) becomes less and less, till we see her again early in the morning as a thin crescent, with its convex edge turned eastwards, and we then finally lose sight of her till after her conjunction with the sun, when the same cycle of changes is renewed.

Now these changes, or *phases*, are easily explained, on the supposition of the moon being an opaque body, made visible to us by light reflected from the sun. On this supposition (which admits of no doubt), the half of the moon's disk turned towards the sun will be illuminated, while only that half turned towards the earth will be visible. If then the moon be in conjunction with the sun, or between the sun and the earth, her dark side is on the whole turned towards us; but being generally either above or below the sun, a small portion of her upper or lower limb is still visible while the crescent changes from the eastern to the western limb. Again, when she is in such a position with respect to the earth and sun, that her disk is *dichotomised*, or half illuminated, the moon is in such a position that the line joining the moon and earth is perpendicular to that joining the moon and sun, the angle formed by these lines having been before acute; and, after this, the obtuseness of this angle still increases till the moon is in opposition, that is, till the earth is nearly in a direct line between her and the sun, when, this angle becoming equal to two right angles, nearly the whole disk is illuminated.

192. The accompanying figure, in which S represents the sun, E the earth, and M the moon in its orbit, will exemplify the changes above described. We here suppose the moon's orbit to coincide with the ecliptic, which is sufficiently correct for the general explanation of the phenomenon. If, also, on the figures of the lunar disk we draw through their centres lines perpendicular to the line S E, the semi-circles thus cut off opposite to the sun represent with sufficient exactness the *orthographic projections* of half the illuminated hemispheres

of the moon, since the whole circle of the lunar orbit subtends at the sun an angle not amounting to half a degree. Also the lines $c' d'$, $c'' d''$, &c., at right angles to the radii vectores, E M, E M′, cut off semi-circles opposite to the earth representing the projections of the hemispheres visible from the earth. The inclination of the lines $c' d'$, $c'' d''$, therefore, in any position of the moon, to $a' b'$, $a'' b''$, will measure the portion of the illuminated surface visible from the earth, and



generally, if we suppose M′ d' to set out from its initial position M b, where the moon is in conjunction, this angle bears the same proportion to two right angles that the illuminated disk does to the whole disk of the moon. But it is evident from what has been said (the sun's distance being so great) that the lines S M′, E M′ are sensibly perpendicular in all cases to b' M′, d' M′, and therefore the illuminated portion is measured by the exterior angle L M′ E of the triangle E M′ S, or, as it is called, by the exterior angle of elongation. Now, on account of the distance of the moon, we see all the parts of her surface orthographically projected on the plane passing through her centre, perpendicular to the line joining her with the earth. Hence it is the *versed sine* of this angle that measures the illuminated surface which we actually see, and this surface will in any case be found equal to moon's surface × versed sine of exterior angle of elongation.

193. If we take the case for which the angle E M′ S is a right angle, or for which the moon is half full or dichotomised, then, since the angular distance M′ E S of the sun and moon can be measured, it is plain that the proportion of the distances E M′ and E S, that is, of the distances of the moon and the sun, can be determined. It was in this way that the astronomer *Aristarchus*, of Samos, in the third century before

the Christian era, formed an estimate (necessarily incorrect) of the relative distances of the sun and moon.

194. There is one phenomenon more of which we must give some account, viz. the *libration* of the moon. This is of three kinds. In the first place, her motion round her axis of rotation is in all probability uniform, and is performed in the same time as that of her revolution in her orbit. This is found to be the case by observations of some of the conspicuous spots on her surface, and hence arises the circumstance that, we always see on the whole the same disk of the moon. But since the motion in her orbit is sensibly unequal, being sometimes faster and sometimes slower than its mean amount, a little more of the eastern and of the western limb is at different times in the course of a revolution brought into view than would otherwise be the case, and this is called the *libration in longitude*.

195. The *libration in latitude* is caused by the axis of rotation of the moon being not exactly perpendicular to the ecliptic, but inclined to it at an angle of about 1° 30′. On this account, in the course of a revolution in the orbit, her northern and her southern poles are alternately presented to us, and a little more of her northern and her southern surface is visible to us in the neighbourhood of the poles than would otherwise be the case.

196. There is a third kind of libration called the *diurnal* libration, which arises from the observer's position on the earth's *surface*, instead of at the *centre*. The moon turns constantly the same hemisphere, not towards a point on the surface, but towards the centre of the earth. Now, on account of the small distance of the moon, the line joining her centre and the earth's centre changes its direction with regard to that joining her centre and the observer's position on the surface as she rises above the horizon. If she were exactly in the zenith, these lines would exactly coincide, but, in any other position, we see more of the surface near the upper limb than we should see from the centre of the earth, and less of the neighbourhood of the lower limb, and by a variable quantity depending on her altitude and distance, that is, on her parallax.

197. We will finally make a few remarks on the physical peculiarities of the surface of the moon, which, on account of her proximity, are better known to us than those of any other body. By the use of good telescopes we see her surface broken up into irregular patches of light and shade, which

evidently indicate inequalities of considerable magnitude. When the sun's light falls most obliquely on the surface presented to us, near the conjunctions for example, we find the boundary of light and darkness not to consist of a regular or well-defined line, but of a series of jagged luminous points, some of which are at a considerable distance from the generally illuminated curve. These are plainly the tops of mountains that catch the first rays of the sun, while the intervening valleys are left in darkness. The heights of some of these which have been deduced by ingenious mathematical processes from micrometrical observations made of them, are very great—in fact, quite equal in that respect to any on the surface of the earth. The lunar mountains, which are extremely numerous, present every characteristic of volcanic formation. They are almost universally of a circular shape, and the larger ones have a hollow within their circular boundary, terminating in a flat bottom, and in some cases having a steep conical hill in the centre. As viewed by Lord Rosse's gigantic reflecting telescope, the flat bottom of one crater is seen to be strewed with blocks or large stones, while the exterior of another is "hatched over" with gullies, radiating towards its centre.*

197*. The science of *selenography*, or the accurate measurement and delineation of the mountains, valleys, plains, and craters of the moon's surface, has advanced with great rapidity during the present century. In the early portion of it, the labours of Lohrmann were of importance; but the publication of the large map (accompanied by topographical description) of Beer and Mädler in 1837, was of itself an epoch in this department of astronomy. These will be yet more valuable in progress of time, for comparison with the results of modern research, in the determination of the question, whether any serious changes are at present taking place on the surface of the moon. A small crater named *Linné*, in the *Mare Serenitatis*, has lately been watched with great interest by astronomers, as there seemed reason to believe that its appearance had changed considerably since the publication of the map before referred to. At the epoch of the map, it was a crater of sufficient importance to make it a point of reference, while, at the present time, during the greater part of every lunation, it is seen only as a patch of light rather brighter than the surrounding surface. At the time

* Outlines of Astronomy, p. 259.

when the sun is rising or setting upon it, however, the walls of the crater are visible, and project shadows.

198. The moon has never been discovered to have on her surface the slightest trace of seas or water of any kind, yet there exist large tracts of apparently allüvial formation, indicating that water must have existed at some previous time. Neither has she any clouds or vapours or any other decisive indications of an atmosphere. This is proved chiefly by the observations of the occultations of stars and of solar eclipses, for the interval of time between the disappearance and reappearance of a star when occulted by the moon, and the time taken in transiting the solar disk during an eclipse, is evidently not affected by such an error as would be produced by refraction of the rays in passing near the moon's edge through an atmosphere of any sensible density. Nevertheless philosophers are not even now all agreed on the total absence of a lunar atmosphere; it is, however, quite clear that if any exist it must be of extreme tenuity, and it is not discoverable by any observations which we can make from the surface of the earth.

199. On account of the slow rotation of the moon, making, that is, a complete revolution in twenty-nine days, the surface is alternately exposed to the heat of the sun unmitigated by clouds or vapours for half that period, and during the other half to the severest intensity of frost. It is evident from these remarkable features of climate, and from the want of an atmosphere, that no inhabitants with physical organs at all similar to our own would be able to exist on her surface. The force of gravity there is also small (only one-seventh) compared with that at the earth's surface, as determined by her mass deduced from very elaborate mathematical discussions of her effect in producing *lunar nutation* by acting on the protuberant matter at the earth's equator; but all the circumstances combined seem to show that nothing like animal life exists there. She gives light to us, and fills our hearts with gratitude to the Giver of all good, for His mercy in thus providing for our comfort and our safety, while a nearer inspection saddens the imaginative mind by presenting the image of a wrecked or a burnt-up planet, perhaps a monument of vengeance in bygone ages on a guilty world, and awaiting the Almighty's fiat to become at some future period equally distant, again a dwelling-place for other organised beings. We cannot close this description of *the surface of* the moon without bringing to the reader's

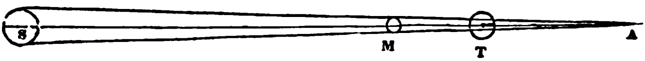
recollection the well-known exclamation of the pious David, which will be repeated with fervour by those who have studied deeply these wonderful bodies, whose motions and properties we have been considering:—"When I consider thy heavens, even the works of thy fingers, the moon and the stars, which thou hast ordained; what is man, that thou art mindful of him? and the son of man, that thou visitest him?" Yet for our benefit the greater light has been given to rule the day, and the lesser light to rule the night.

200. In connection with the motions of the sun and moon, it will be expected that we give some explanation of the eclipses of those bodies. This we shall do in few words, referring the reader for fuller information to Sir J. Herschel's "Outlines of Astronomy," or other popular works, since our necessary limitation of space enables us to give only an outline of the leading features and principles of astronomy, without dwelling much on the details of the *casual* phenomena resulting from the motions of the heavenly bodies.

201. Since the inclination of the lunar orbit to the ecliptic is small (only 5°), and since there are more than twelve conjunctions and twelve oppositions of the moon with the sun in the course of every year, it follows that there is a very great probability of the sun, the earth, and the moon being so nearly in a straight line at some of these times of conjunction or opposition as to produce an eclipse of the sun or the moon. If this should take place when the moon is in conjunction with the sun (that is, at new moon), it is plain that she will pass directly between us and that luminary, and prevent either the whole or part of his light from reaching us, or there will be an eclipse of the sun. But since by parallax she is depressed on the visible sphere of the heavens by a large quantity depending upon the geographical latitude, while the place of the sun, on account of his great distance, is in a very trifling degree affected, it is plain that an eclipse of the sun may take place at one point of the earth's surface, while there is no eclipse at all at another, or it may be total or annular at one place, and only partial at another. Thus the great eclipse of 1851 was total for parts of Sweden, Norway, Prussia, and Poland, while at Greenwich it was only partial. Now, for finding the circumstances of a solar eclipse, that is, for determining whether it will be *total* or *annular*, and for finding those parts of the earth's surface at which it will be total or annular, and at which it will be only partial, it is necessary to remark, that the cone which would envelop the

sun and moon at the time of a solar eclipse, that is, which would be formed by a series of tangents to their surfaces, has its apex situated very nearly at the distance of the earth from the sun, being carried a little farther off, or a little nearer, accordingly as the moon happens to be nearer to or farther from the earth, or near perigee or apogee. If the moon be in or near to perigee, the apex of the cone will lie farther from the sun than the earth is, as in fig. 1, where S, M,

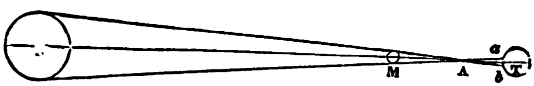
Fig. 1.



and T represent the sun, moon, and earth; and the part of the earth's surface intersected by the cone during the progress of the moon across the sun's disk, gives the geographical boundaries of the eclipse, within which a total eclipse may take place, and near the centre of which it *must* take place.

202. If, however, at the time of the eclipse the moon be near *apogee*, the apex of the cone will lie between the sun and the earth as in fig. 2, and the sheet of the cone produced will meet the earth's surface, as at *a*, *b*. Hence a

Fig. 2.

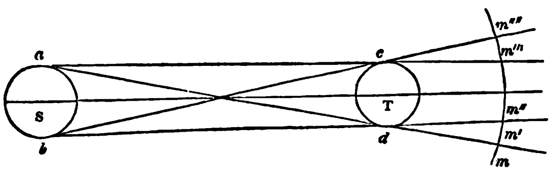


person at *a* will see the upper part of the sun, but the moon's lower limb will appear to graze the sun's lower limb; while an observer at *b* will see the lower part of the sun, while the moon's upper limb appears to graze that of the sun. Between *a* and *b* an observer will see a little of the upper and lower limbs, or the eclipse will be annular.

203. Thus far we have spoken of annular and total solar eclipses, which occur when the moon is very near the node of her orbit at the time of conjunction. If she be at a greater distance from the node, a partial eclipse will take place at some parts of the earth's surface, while none at all may take place at others. The sun may also at the time of an eclipse be beneath the horizon, or it may occur during *the night, and will*, of course, to such places be invisible.

204. If the moon be near her node at *opposition* (or full moon) a *lunar eclipse* may take place by the interposition of the earth preventing the light of the sun from reaching her. Hence the cone used in illustration must be supposed to envelop the sun and earth, and the position of the moon with regard to its axis in passing across the shadow thus thrown upon her will determine whether the eclipse is total or partial. If she be very near her node at the time of opposition, a total eclipse will take place equally to every part of the earth's surface at which she is above the horizon; but if she be at some distance from the node, a partial eclipse or none at all will take place.

Fig. 3.



If in fig. 3 we draw tangents on the same and opposite sides of the earth's surface (T) from the sun (S), viz., *a c*, *a d*, and *b d*, *b c*, it is plain that between *a c* and *b d* no light of the sun can extend, but that between *a c* and *b c* produced, as also between *b d* produced and *a d* produced, part of the light of the sun can reach, and a *penumbra* will be formed during the progress of the moon from m to m'''' between m' and m'', and again between m''' and m'''', when her surface will be only obscured, but that from m'' to m''', while she is in the *umbra*, or real shadow, the whole or part of her surface will be invisible.

ing or diminishing with very variable velocities. If the apsides are in syzygy, the excentricity is at its greatest value, and stationary; if, on the contrary, the apsides be in quadratures, the excentricity has its least value, and is also stationary; finally, it diminishes while the sun is moving from the syzygy position of the apse till it is at right angles to the line of apsides; and it increases from this position till the apse is in syzygy again. Hence, since the equation of the centre depends on the excentricity, there will be an inequality introduced depending on the moon's mean anomaly, as well as on her distance from syzygy. This is the evection, the largest of the lunar inequalities, and it has for its argument, as has been stated, twice the difference of the longitude of the moon and sun *minus* the moon's mean anomaly. We have no space to go through the whole of the reasoning for the explanation of all the inequalities, and, indeed, the reader will find them all admirably discussed in Airy's "Gravitation," forming one of the articles in the "Penny Cyclopædia," but reprinted in a separate volume. We will simply mention in few words the conclusions arrived at with regard to the three great inequalities, the *evection*, the *variation*, and the *annual equation*. The former, that is, the *evection*, is dependent upon the position of the line of apsides, and is derived from two effects of the sun's disturbing action, viz., the irregularity of the motion of the perigee, and the periodical alteration of the excentricity of the orbit: the *variation* arises from the action of the tangential force, which forces the orbit, supposed circular, into an oval shape, and alternately diminishes and increases the velocity; it depends, therefore, upon the distance of the moon from the syzygies; finally, the *annual equation* arises from the excentricity of the earth's orbit, which causes the sun's distance to vary, and the disturbing force in consequence to vary, at different periods of the year; its period is therefore annual, and hence its name.

We have shown the form in which the *evection* is introduced into calculation.

The *variation* amounts at its maximum to about 35′ 41″·6, and has for its argument the sine of twice the difference of longitude of the sun and moon. It was discovered by Tycho Brahe about the year 1590.

The *annual equation* amounts at its maximum to 11′ 11″·97, and has for argument the sine of the sun's mean anomaly. It was also discovered by Tycho Brahe about the year *1590.*

190. For computation of the moon's true longitude, we have then, neglecting minor inequalities,—

$$\begin{aligned}\text{True longitude} = {} & \text{mean longitude} \\ & + \text{Equation of centre} + \text{Evection} \\ & + \text{Variation} + \text{Annual equation,}\end{aligned}$$

which will become, if we put E to denote the moon's mean longitude at a given epoch, M her mean anomaly, reckoned from apogee, and ☽ and ☉ the moon's longitude and the sun's—

$$\begin{aligned}\text{True longitude} = {} & E - 6^\circ\ 17'\ 54''\cdot 40 \times \sin. M. \\ & - 1^\circ\ 20'\ 29''\cdot 5 \times \sin. [2\,(☽ - ☉) - M\,] \\ & + 35'\ 41''\cdot 6 \times \sin. 2\,(☽ - ☉) \\ & + 11'\ 11''\cdot 97 \times \sin. ☉\end{aligned}$$

In the preceding discussion of the orbit described by the moon round the earth and its irregularities, we have only endeavoured to familiarise the student with some of the leading features of the lunar theory, as preparatory to the complete and philosophical popular explanation which he should seek for in the reading of Airy's "Gravitation." In that treatise not only the perturbations of the moon, but the planetary perturbations generally, are fully discussed, by means of reasonings deduced from the simplest principles of mechanics, and without the use of a single algebraical expression. It is, therefore, capable of being studied by any one possessed of ordinary abilities, and should be neglected by no student who aims at a clear conception of those complicated laws of planetary movement arising from their mutual perturbations, which he will afterwards have to develop to their remotest consequences by the most refined and difficult processes of analysis.

191. We will now proceed to a much easier and more obvious subject, viz., the *phases* of the moon. In watching the moon through a lunation, we not only observe a rapid orbital motion from west to east amongst the stars, but (evidently in connection with this orbital motion) a change of figure and magnitude of the illuminated portion of the disk. For example, after missing her light for several evenings, we observe her at a short distance following the sun in the form of a thin crescent, with its convexity turned towards him. From evening to evening, as she separates from the sun by her relative easterly motion, the crescent increases in magnitude, till the line joining the horns is

activity of the present age, and particularly of the attention which has been devoted to Astronomy, the number known at present is two hundred and thirty-three. Of these additional planets, four were discovered about the beginning of the present century, two hundred and twenty-two since the year 1844, of which all but one, like the four just mentioned, lie between the orbits of Mars and Jupiter, and are of much smaller size than the rest; the remaining one is the planet Neptune, exterior to all the rest, whose discovery is one of the greatest intellectual triumphs of our age.

209. Before the discovery of Neptune, which will be treated of a few pages farther on, the mean distances of the planets from the sun were observed to obey a very curious empirical law (called Bode's law, that astronomer having first noticed it), which may be thus expressed. Call the distance of Mercury 4, then that of Venus is $4 + 3 = 7$; that of the Earth is $4 + (3 \times 2) = 10$; that of Mars $= 4 + (3 \times 2 \times 2) = 16$; that of the small planets $= 4 + (3 \times 2 \times 2 \times 2) = 28$; and so on, the distance of Uranus being 196. But, for the next planet, the distance thus computed would be 388, which, the reader will perceive by inspection of the table which follows, is considerably too great. Now, in the calculations made by Adams and Le Verrier previously to the discovery of Neptune, it was absolutely necessary to assume arbitrary values for the mean distance of the supposed disturbing planet, and there was no clue whatever to guide these mathematicians in their assumption, except that afforded by Bode's law. It thus happened that several sets of calculations were found necessary, the assumed value being continually lessened, before the conditions of disturbance were satisfied, and even at the last the distance finally assumed proved to be too large. It is therefore an even question, whether the law was of any service in the calculations or not, but at all events it formed a kind of basis for the commencement of the work, and the errors of the assumptions were necessarily capable of correction by the processes employed.

210. It will be convenient to give here a table of the periods, comparative distances, and some of the orbital elements of the principal planets of the solar system.

TABLE OF THE NAMES, SYMBOLS, PERIODS, COMPARATIVE DISTANCES, AND SOME ORBITAL ELEMENTS OF THE PRINCIPAL PLANETS.

Planet.	Symbol.	Period.	Comparative Mean Distance from the Sun.	Eccentricity of Orbit.	Inclination of Orbit to Ecliptic.
		Days.			° ′ ″
MERCURY .	☿	87·969	0·38710	0·20560	7. 0. 8
VENUS .	♀	224·701	0·72333	0·00684	3.23.35
EARTH .	⊕	365·256	1·00000	0·01677	0. 0. 0
MARS . .	♂	686·980	1·52369	0·09326	1.51. 2
JUPITER .	♃	4332·588	5·20280	0·04825	1.18.41
SATURN .	♄	10759·236	9·53886	0·05607	2.29.40
URANUS .	♅	30688·390	19·18338	0·04636	0.46.21
NEPTUNE .	♆	60181·113	30·05437	0·00899	1.46.59

It has been concluded from theory that there is a planet (perhaps more than one) revolving round the Sun within the orbit of Mercury; and it has even been supposed that one or more such bodies have been seen. Indeed the name Vulcan has been proposed for one believed to have been observed on a particular occasion; but it was somewhat premature thus to name a body the existence of which (still less any of the circumstances of its motion) cannot be said to have been proved.

At mean distances from the Sun greater than that of Mars and less than that of Jupiter, revolve a large group of very small planets, of which there are now known to be 225 members, and probably the actual number is much greater. Four of these were discovered early in the century; 81 between the years 1845 and 1865; 62 from 1866 to 1875; and 62 more from 1876 to 1880. In 1881 only 1 was discovered; in 1882 up to the time we write (May 9th), 5. These last six have not yet been named.

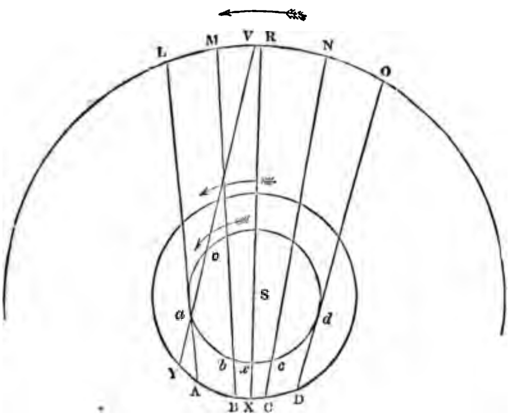
When the first edition of this book was written, in 1851, only fifteen members of the large group of small planets were known to exist. So rapid has the progress of discovery since been that, as has been already stated, no fewer than two hundred and twenty-five are at present known, and as we have said, the probability is that the actual number is much greater even than that.

211. Those planets which move in orbits nearer the sun than that of the earth are called *inferior planets*, while those moving beyond the earth's orbit are called *superior planets*. And we propose, before giving an account of each separate planet, to explain their *apparent* motions in the heavens, as seen from the earth, and afterwards to show by what means their *real* motions round the sun can be deduced from observation, and the elements of their orbits calculated.

212. We commence with the inferior planets, and we will take Venus as our example, this planet being familiar to all our readers as the most beautiful object in the heavens next to the moon. When the light is fading on a fine evening we see her shining in the west with a light incomparably superior to that of any of the other planets, and for some time she seems to retain a fixed position in the heavens. Her brilliancy increases as she approaches the sun, that is, as she appears on each successive evening at sunset nearer to the horizon, till she becomes lost in the sun's rays, and is missed for a time. After this, if any of our readers would take the trouble to rise before the sun, they would see her shining with the same brilliancy in the east, and on successive mornings would find her at a still greater distance, and rapidly separating from the sun. After a considerable time she would be found to become stationary again, and then, decreasing in brilliancy, to move in the contrary direction to meet the sun again, and, after a time, she would be for the second time lost in his rays. We will now illustrate, by means of a diagram, these oscillating motions, and show how they are natural geometrical consequences of her motion in an orbit smaller than that of the earth.

In the annexed figure let the inner circle represent the orbit of Venus; the middle one that of the earth; and the outer one the circle of the heavens. The directions of the arrows represent the directions of orbital motion round the sun, and of *direct* motion (that is, motion in the order of the signs of the zodiac) in the heavens.

Imagine Venus to come from *v*, moving in the direction *v a b c d*, while the earth is moving from Y in the direction Y A B C D. When Venus is at *v* she will be seen projected on the heavens at V, and when she is at *a* (the earth being at A), she will appear at L, having appeared to describe the *direct* arc V L. At *a*, however, she is moving in the direction of the line joining her and the earth —this position is called her point of greatest elongation from the sun, and some time after arriving at this point she will become stationary. The stationary point is determined by the consideration that the resolved parts of the motions of the

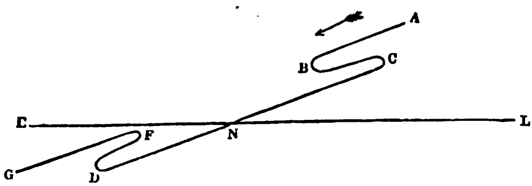


planet and the earth perpendicular to the line joining them must be equal. But after this, while she is still approaching the earth, and therefore becoming more brilliant, if we take *a b*, A B, for arcs described by her and the earth in equal times, *a b* being considerably larger than A B, she will be seen at M, having appeared to retrograde through the arc L M. All this time she is to the east of the sun, or is visible in the evening, but after a time her motion will gain upon the earth's motion, till, arriving at *x*, she will pass the meridian at the same time as the sun, or be in inferior conjunction, and nearest the earth: she then passes to the other side of the sun and becomes a *morning planet*, and separates from him rapidly till she comes to *d*, before which she is again stationary; after this she proceeds towards *superior conjunction* with the sun, when she is at her farthest distance from the

earth. The cycle of changes is then renewed in the same order.

213. It is evident from what has been said above, that Venus, as seen from the earth, never separates very far from the sun, but describes small arcs in the heavens, sometimes going a certain distance to the east and sometimes to the west of him. If the earth were quite stationary, this angle would be determined by drawing tangents from it to her orbit, but the earth's motion modifies the apparent separation, and she sometimes passes the meridian earlier than nine o'clock in the morning, and sometimes later than three in the afternoon, the equation of time conspiring to make the angular separation measured in time appear greater than it really is.

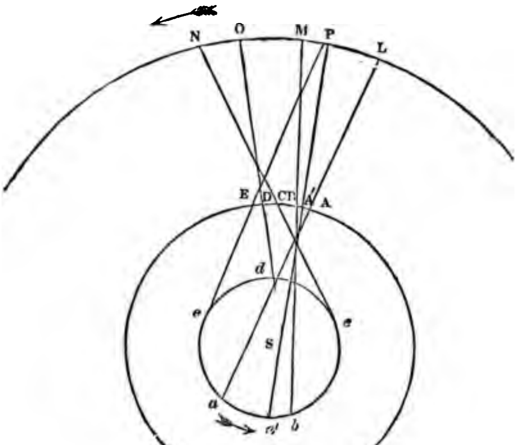
214. The apparent motions of the superior planets are different from those of the inferior, but admit of an equally simple explanation. If we were to map down the projected motions of any one of them, Jupiter for example, from year to year, we should find the projected path to be something



like that represented in the figure, where a straight line represents the projection of the ecliptic. The motion would appear to be *direct* through A B, stationary at B, retrograde through B C, then stationary at C, and then again direct through C D, crossing the ecliptic at N, and so on. It would appear, in fact, to describe a zigzag path very little inclined to the ecliptic, sometimes retreating and sometimes advancing, but on the whole gaining in direct motion. At certain times, for instance, we should find it in opposition with the sun, that is, the sun and planet would be on the opposite side to the earth, the three being nearly in a straight line; and at such times the *geocentric* and *heliocentric* longitudes (that is, the positions with regard to the first point of Aries measured from the centre of the earth and the centre of the sun) are the same. The observed arcs therefore obtained by comparing the observations made at successive oppositions will give the real advance of the planet in its orbit, notwithstanding its intermediate retrogradations.

215. We will now see how these motions are explained on the supposition of Jupiter describing an orbit exterior to that of the earth. Illustrating by a diagram, as before, let the inner circle represent the orbit of the earth, the middle one that of Jupiter (the disproportion of the orbits is, for convenience, not adequately represented), and the outer one a section of the sphere of the heavens.

Let the earth and planet be at the same time at *a* and A, and, while the earth describes the arc *a b*, let the planet describe A B; the places of the planet will then be referred to the points L and M. It will therefore have appeared to describe the arc L M in the order of the signs, or with direct motion, and in this time it will have passed conjunction with the sun at some intermediate position, A′. Hence on either side of conjunction the apparent motion of a superior planet



is direct. Let now *c* and C be positions of the earth and planet when C *c* is a tangent to the earth's orbit, the planet will evidently then appear stationary soon after passing N; but, after arcs *c d*, C D, have been described by the earth and planet, the latter will be referred to the point O, having appeared to move backwards or to retrograde through N O. It will then become in opposition with the sun (that is, the planet and sun will be on opposite sides of the earth at an interval of 180° of geocentric longitude), and will continue

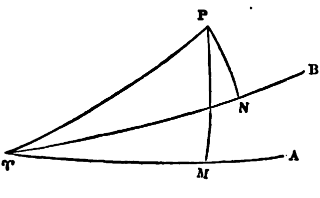
to retrograde till it arrives nearly at E, the earth being at *e*, where the line joining it and the earth is again a tangent to the earth's orbit, before passing which point it is again stationary. It will then begin to move *directly*, or according to the order of the signs, and so on for another revolution of the earth.

216. From the above considerations we derive the following rule:—

The inferior planets retrograde before and after inferior conjunction, and move directly in the rest of their orbits: the superior planets move directly before and after conjunction, and retrograde before and after opposition.

217. We will now show how the places of the planets as referred to the sun can be obtained from the geocentric observations.

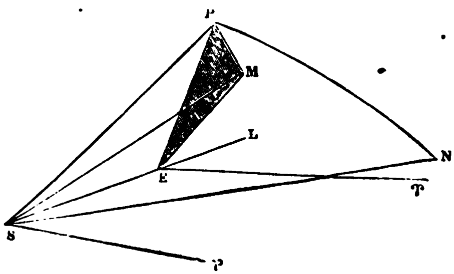
We must again remind the reader, that the observations made with the fixed instruments of an observatory are those of Right Ascension and North Polar distance, and that these observations, before they can be used, require correction for refraction, parallax, aberration, and the motion of the equinox. They may then be considered as made at the earth's centre, and referred to a fixed equinox and a fixed equator. Now the position of the ecliptic with regard to the equator is known with the utmost accuracy, being derived from observations of the sun made near the equinoxes and solstices. At this present time, for example, the mean value of the obliquity is nearly 23° 27⅓′, and has a small secular diminution amounting to 0″·457 per year. It is then easy to reduce to the ecliptic the observed positions of the body referred to the equator, that is, to convert the observed Right Ascensions and North Polar distances to geocentric longitudes and ecliptic polar distances, or to geocentric longitudes and latitudes.



Thus, if ♈ A and ♈ B be portions of the equator and ecliptic, and P the position of a planet, then, if perpendicular arcs P M, P N be drawn to the two planes, ♈ M and P M will be the Right Ascension and declination, and ♈ N and P N the geocentric longitude and latitude of the planet, and it is a very easy problem in spherical trigonometry to deduce the latter in terms of the

former, and of the known obliquity N ♈ M. We have then the place of the body referred to the plane in which the relative motions of the earth and sun are performed; and the next process is to deduce the heliocentric longitude and latitude from the geocentric, that is, to refer the body's place to the sun, which is its proper centre, instead of the earth.

218. Let S, E, and P be the position of the sun, the earth, and a planet at a given time when the geocentric place of th latter is known; draw S ♈, E ♈ towards the vernal equinox, parallel to each other in the plane of the ecliptic, and P M perpendicular to the plane, and join S M, E M; then the



angles M E ♈ and M S ♈ will represent the geocentric and heliocentric longitudes, and P E M and P S M the corresponding latitudes. Also the geocentric co-ordinates, that is, the latitudes and longitudes as seen from the earth's centre, being found from observations, the heliocentric longitude and latitude, and the distance of the planet from the earth, can easily be expressed in terms of them, and of the known distance of the earth from the sun, and earth's longitude.

219. We have before had occasion, in treating of the solar motion, to mention the elements of a planet's orbit, but we will proceed now to speak of them more particularly.

It is plain that the position of the planet (to whatever points or planes we may refer it) will depend—

First, upon the position of the plane in which it performs its orbit.

Secondly, Upon the magnitude, figure, and position of the ellipse which it describes in this plane.

Thirdly, Upon its position in the circumference of this ellipse.

Now, referring, as usual, everything to the plane of the ecliptic, the position of the plane of the orbit will be defined

by the *longitudes* of the points or *nodes* where it meets the ecliptic, and by its angle of inclination to the ecliptic: the position of the major axis or lines of *apsides* of the ellipse will be defined by the longitude of the perihelion or aphelion: the magnitude and form of the ellipse will be defined by the semi-major axis, or mean distance as it is called, and by the excentricity or ratio which half the difference of the greatest and least distances bears to the mean distance; and, finally, the place of the planet in the ellipse will be known by means of its known position or longitude at some given time or epoch, generally called, for brevity, the epoch of longitude.

Hence the *six* quantities or elements which determine a planet's position are:—the *longitude of the node*, and the *inclination of the orbit to the ecliptic*, the *longitude of the perihelion or aphelion*, the *mean distance*, and the *excentricity of the orbit*, and finally, the *epoch of mean longitude*. To these may be added the *argument of latitude*, or the angular distance of the planet from its node, measured along the orbit, which can be computed immediately from the node and inclination.

220. The way in which these elements must be treated differs considerably for the old or well-known, and for newly-discovered planets. For the former, *i.e.* Mercury, Venus, Mars, Jupiter, and Saturn, which were known and observed in ancient times, their elements were found and repeatedly corrected by observations made at long intervals of time, and by taking advantage of such circumstances of their motion as were most favourable for the discovery of particular elements. For example, the mean motion or sidereal period can be discovered with very great accuracy by observing the successive passages of the body through its ascending or descending node. For by reducing the observed right ascensions and declinations to geocentric latitudes and longitudes, it can be found when the latitude is about to become *nothing*, or the body is about to cross the ecliptic, and, by observations made before and after this period, the exact moment at which it was in the node can be found by simple proportion, its motion in latitude being at this time nearly uniform for short intervals. Hence the longitudes of the ascending and descending node will be known also. The inclination of the orbit to the ecliptic can also be found by observing when the latitude arrives at its maximum. We have also shown how the solar parallax has been accurately determined,

and this, in connection with Kepler's Third Law, gives at once the dimensions of all the orbits, when the periods of revolution are known.

Now, by the geometrical relations existing between the geocentric and heliocentric latitudes, longitudes, &c., in the preceding figure, we can with great ease express the argument of latitude in terms of the longitude of the node and the inclination, and of the geocentric longitudes of the planet and the sun; secondly, the distance of the planet from the earth can be expressed in terms of the sun's distance from the earth, the argument of latitude, and some of the above elements; and lastly, the radius vector of the planet, or distance from the sun, can be found in terms of previously known quantities, as also can the heliocentric longitude and latitude. By such means a series of observed distances from the sun in the elliptic orbit will be obtained, and by assuming an ellipse of a certain excentricity, and with a certain longitude of the perihelion which shall nearly represent all the distances, an approximation will be made to the remaining elements. These elements will then be corrected by computing the heliocentric places of the planet corresponding to the times of other observations, and comparing them with the heliocentric places deduced from geocentric observations in connection with the assumed elements. Equations of condition will then be obtained for determining the errors of the assumed elements to any degree of accuracy.

221. For unknown planets, every geocentric observation will, by a somewhat similar treatment, give two equations subsisting between the known geocentric quantities and the symbols expressing the elements. Hence three observations will give six equations, sufficient for determining the *six* elements of the orbit. Thus, in the greater number of instances of the recent discoveries of the small planets between Mars and Jupiter, no sooner were three complete observations announced than one or more of the zealous and able astronomers attached to the various observatories in Europe or America have immediately furnished elements of the orbit, and *ephemerides*, that is, tables of daily right ascensions, and declinations computed from the elements thus found, for the use of astonomers who might wish to follow the planet and make more numerous observations of its position.

We cannot expend more space upon this rather difficult subject, and we must devote the remainder of this chapter to

the principal peculiarities of the separate planets of the solar system.

222. The planet MERCURY is too near to the sun to allow us to make any very accurate observations of the shape and other peculiarities of its surface. It has certainly no considerable ellipticity, that is, it is very nearly round, as the author has ascertained by micrometrical measurement. Its apparent diameter varies from 5″ to 12″, and its real diameter is about 2,990 miles. From doubtful observations of some spots on its surface it is supposed to revolve on its axis in about the same period as the earth, and in the same direction. Its mass is rather less than one-twelfth part of the earth, and its mean density is rather greater than that of the earth. The force of gravity at its surface is about one-eighth of that at the surface of the earth. It exhibits phases like the moon, and from a similar cause. The excentricity of its orbit is large, being about 0·205, and the inclination is also large, being 7°. Its excursions on each side of the sun do not much exceed 18°. Supposing all our heat to come from the sun, it is calculated that the mean heat in Mercury is above that of boiling quicksilver, and even near his poles water would always boil. The sun's diameter would appear from his surface more than twice as large as from the earth.

223. VENUS is a far more interesting planet, and, on account of her greater distance from the sun, admits of more frequent and accurate observation. Her light in a telescope is, however, so dazzling and brilliant, that, by exaggerating all the defects of the telescope, physical observations of the surface are difficult. By means of the rotation of spots imperfectly seen on her surface by the German astronomer Schroeter, the time of rotation on her axis is imagined to be rather less than that of the earth, and also from west to east. The phases, which are exactly similar to the moon's, only with much longer periods, are very interesting when viewed through a telescope, and her brightness is such as to render her occasionally visible at mid-day with the naked eye (as was the case in the year 1868), when her position with respect to proximity to the earth is most favourable. The excentricity of the orbit is very small, and the inclination does not amount to 3½°; her apparent diameter sometimes amounts to 1′, and her real diameter is about 7,660 miles. She seems to be surrounded by an atmosphere which may probably mitigate to her inhabitants, if she have any, the intense heat of the sun, which yet must be far too great for

the existence of plants or animals like those existing on the earth. Her mass is rather greater, and her density rather less, than that of the earth. Hence the force of gravity at her surface is about the same as on the surface of the earth. The reader will not forget the important service rendered to astronomers by this planet, in furnishing a means of ascertaining the solar parallax, by her transits across the sun's disk.

224. Venus being so near the earth, it might be expected that she would produce disturbances both in the orbit of our own planet and of its satellite the moon. Such is, in fact, the case. An inequality, having a very long period, in the motions of the earth and Venus, was discovered many years ago by Airy, and a curious inequality in the lunar orbit, arising from the attraction of Venus, was subsequently discovered by the late Prof. Hansen, of Gotha.

225. MARS, the nearest of the planets exterior to the earth, that is, of the superior planets, offers more points of similarity than any of the others. The excentricity of the orbit is, however, considerably greater, being rather less than $\frac{1}{10}$. The inclination to the ecliptic is 1° 51′. His diameter is about 4,210 miles; when in opposition to the sun, that is, nearest to the earth, his apparent diameter is about 23″; and the ellipticity, as resulting from eighteen sets of measures made by the author with the Oxford heliometer at the opposition of 1862, is $\frac{1}{47}$. As, however, the time of rotation is very nearly the same as that of the earth, whose ellipticity is only

$\frac{1}{300}$, this result seems to require additional confirmation, though the correctness of the measures appears to be unquestionable. The disk is so well seen through good telescopes, that rude maps of his surface have been drawn, in which something like a vague delineation of seas and continents is exhibited. The colour of the darkest part is that of

a brownish red, and near the poles is a zone of white, indicating the existence of snow in large quantities. In the accompanying engraving the distinctness of the white spot near the south pole is exaggerated, but it was very marked when the drawing was made. His climate must be considerably colder than our own, but, as the inclination of his axis to the ecliptic is nearly the same as that of the earth, and the period of diurnal rotation ($24^h\ 37^m$) only a trifle larger, the changes of the seasons must, in many respects, be very similar to those here. His mass is about $\frac{1}{7}$ part of that of the earth, and his density a little smaller. The force of gravity at his surface is about $\frac{4}{7}$ of that at the surface of the earth. He appears to be surrounded by an atmosphere of considerable density. In the year 1877 it was discovered by Prof. Asaph Hall, of Washington, that this planet is accompanied by two very small satellites, which he afterwards named Deimos and Phobos respectively.

226. Of the small planets between Mars and Jupiter we know very little, except their orbital motions. Some of them are exceedingly minute, their surfaces being not much larger than a large estate. The brightest is Vesta, which appears when nearest to us like a star of the sixth magnitude; the others vary generally from the 7th to the 13th magnitudes, according to their distance. The discovery of the earlier ones had its origin in a curious speculation, arising from the failure of Bode's law between the orbits of Mars and Jupiter, which led to the idea of a large planet having been shattered to pieces. An Association of Astronomers was formed therefore to search in the most likely parts of the heavens for the supposed fragments, and not long afterwards four small planets were discovered, viz. Ceres, Pallas, Juno, and Vesta, the first being found on the very first day of the present century, (January 1, 1801), and the last on March 29, 1807. It was not until 1845 that the next, viz. Astræa, was discovered by the late Herr Hencke, of Driesen, in Prussia, who also discovered Hebe, in 1847. Mr. Hind discovered Iris and Flora later in the latter year, and Mr. Graham, Metis, in 1848. From that time no year has elapsed without the discovery of at least one, and in the year 1879 no less than twenty were discovered. As has been already mentioned, the number of known bodies of this class now amounts to two hundred and twenty-five.

When the orbits of all of them are known with greater accuracy, a projection of them will show better whether the

original idea of the explosion of a large planet is tenable or not. Astronomers at present are rather divided in opinion on this subject, though the investigations which have been hitherto made are on the whole unfavourable to the theory.

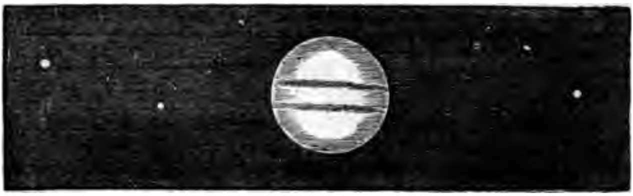
227. We should not omit to mention, in connection with this subject, the zodiacal star-maps constructed by the late Dr. Bremiker, of Berlin, in which the positions of all stars down to the tenth magnitude within the zodiacal limits are represented, as these maps have not only materially assisted in the discovery of these small planets, but the planet Neptune was by means of them recognised immediately when the telescope of the large equatorial at Berlin was directed by Dr. Galle towards the position indicated to him by Le Verrier. A series of such charts of stars observed by Mr. Bishop and Mr. Hind, in the Regent's Park, has also been published, and as a third set we may mention those made by the late M. Chacornac, at the Paris Observatory.

228. The orbits of these small planets differ from those of the large planets previously known chiefly in their inclinations, which are not included within the zodiacal limits, but are many of them very large, and this feature renders the computation of their perturbations by the large planets very intricate and difficult. A method of calculation devised by the celebrated astronomer Hansen has, in a great measure, conquered this difficulty, and considerably extended the power of analysis in the computation of the places of the planets generally.

229. Jupiter, the largest, and in many respects the most important, of all the planets, is next in order of distance from the sun; the sidereal period is 4332·584 days, and his synodic period, that is, the interval between his successive conjunctions with the sun, is 398·867 days. The inclination of his orbit to the ecliptic is 1° 19′ nearly, and the excentricity is 0·04818. His mean distance from the sun is rather more than five times that of the earth.

230. The shape of this stupendous globe is plainly elliptical, even to a casual observer, when viewing him through a good telescope, and the ellipticity, as deduced from a great number of careful observations made by the author at Greenwich and Oxford, is about $\frac{1}{18}$. The time of revolution on his axis, as determined by certain spots at times visible in his atmosphere, is $9^h\ 55^m\ 50^s$, and the ellipticity calculated from this time of rotation, on the supposition of the original fluidity of the globe, corresponds pretty accurately

with the observed ellipticity. The angular mean diameter, or axis major of this ellipse, is about 40″, which corresponds to a real diameter of about 86,000 miles, nearly eleven times the diameter of the earth. The mass is about $\frac{1}{1047}$ (that of the sun being unity), as determined by Airy from the ob-



served elongations of the fourth satellite (see page 84); that is, the mass is upwards of 310 times that of the earth, but the density is not quite one quarter of that of our planet. The force of gravity at the surface is about $2\frac{3}{5}$ times that of the earth.

231. The disk of Jupiter is crossed by dark bands, or *belts* as they are generally called, above and below the equator, as is denoted in the figure. These belts suggest the idea of, and there is little doubt that they owe their origin to, disturbances in the atmosphere surrounding the planet. They vary much at different times in breadth and situation, and are evidently not of a rigid or permanent character.

232. Jupiter is attended by four satellites or moons revolving round him from west to east, in the same way as the moon does round the earth, according to the law of gravitation. These satellites suffer eclipses on entering into the shadow of Jupiter, and are occulted or hidden when they pass behind his body; they are also observed to pass over or to *transit* his disk, and at such times their shadows can be seen like black spots passing along the disk. On entering on the body of the planet, they can be distinctly seen when near the border, by their superior brightness, but they are lost sight of when approaching the centre: this proves most distinctly that the border is *shaded*, and indicates an atmosphere of some density. The times of the eclipses, when observed at different places on the earth's surface, determine directly the difference of longitude of the places, since they must occur at the same moment of *absolute* time, the observations being given in terms of *local* time. It was also by means of eclipses of the satellites at times when Jupiter was *at very different* distances from the earth that Römer dis-

covered the successive propagation of light, and determined its velocity.

233. To an observer on Jupiter, the first satellite would appear rather larger than our moon, the second rather more than half as large, the third rather larger than the second, and the fourth not half so large. Their actual diameters are about 2,800, 2,200, 3,700, and 3,250 miles respectively.

234. The mean motions and times of revolution of the first three satellites are connected by a singular law; viz., that the angular velocity of the first added to twice that of the third is equal to three times the angular velocity of the second. And hence we might easily prove that if "from the mean longitude of the first added to twice that of the third there be subtracted three times the mean longitude of the second, the remainder will be a constant angle." This constant angle is found to be equal to 180°.

235. The above remarkable relation between the mean motions of the satellites leads to this interesting result, viz., that they cannot all be eclipsed at the same time; that is, that even in extreme cases Jupiter will never be deprived of the light of all his moons at once. We need do no more than indicate to the reader, without further remark, this proof of beneficent wisdom.

236. The first three satellites move very nearly in the plane of Jupiter's equator, in orbits very nearly circular. The inclination of the fourth to the equator is about 8°, and its excentricity is large. In consequence, when the fourth satellite is seen to pass across Jupiter's body or behind it, the apparent path is frequently very far from the centre. Indeed it occasionally happens (and the author of this little book had opportunity of watching one such transit) that the satellite merely grazes the upper part of the disk, so as never to cease to be at least partially visible during the whole time.*

237. The mass of Jupiter being so great, it might be naturally expected that his influence would be considerable in disturbing the other planets, and this is really the case. But the most curious circumstance in the disturbances produced by him is the reciprocal effect produced in the motions of himself and Saturn, his neighbour in the heavens, and almost rivalling him in bulk. An equation or disturbance, having a very long period of about 918 years, is produced by the mutual actions of these immense bodies, of such

* See *Greenwich Observations* for 1844, p. 138.

a nature that if one be, by the disturbance, put *before* its mean place, the other will be *behind* its mean place. At present, the motion of Saturn is accelerated by the disturbance, and that of Jupiter retarded, but in the seventeenth century the circumstances were reversed, and Saturn was retarded, while Jupiter was accelerated. This inequality, known by the name of "the great inequality of Jupiter and Saturn," is of such a magnitude as at its maximum to advance or retard Saturn by about 0° 49′ in longitude, and to retard or advance Jupiter by about 0° 21′. We have not space, nor does it fall within our plan, to trace the physical cause of this remarkable effect of disturbing action, but the reader may be assured that a general explanation can be given in much the same way that has been used for the inequalities of the moon. The more advanced reader may consult Sir J. Herschel's "Outlines of Astronomy."

238. The next planet is SATURN, not inferior in general interest to Jupiter, and of equal importance in the planetary theory. His most remarkable appendage is a luminous ring, by which he is generally seen to be surrounded. This ring is opaque, as is proved by the shadow of it which is thrown on the body of the planet, and there is little doubt now that it is in fact composed of a cloud of little satellites too small to be separately seen in the telescope, and too close together to admit of the intervals between them being visible. By its parallelism with the belts with which Saturn as well as Jupiter is striped, it appears that the axis of rotation of the planet is perpendicular to the plane of the ring, and observations of spots on the surface of the planet give for the time of his rotation about $10^{h}\ 15^{m}$. The ring, till lately, was known to be divided into two distinct portions, separated by a dark interval easily seen in good telescopes, but recently a discovery has been made of the existence of a *third* ring inside the other two. This last, which requires the best state of the atmosphere and a very good telescope, as well as an experienced observer, to be rendered visible, reflects light so imperfectly that its existence was not known till the month of November, 1850, when the late Mr. G. P. Bond, of the Cambridge Observatory, Massachusetts, detected a luminous appearance which subsequent observations by himself and his father showed to be due to this interior dusky ring. Before intelligence of this reached England, that acute observer, the late Mr. Dawes, noticed a similar appearance at Wateringbury, near Maidstone. It should be remarked that so far back as

1838, Dr. Galle had noticed a gradual shading off of the ring towards the ball, and indeed there is reason to believe that something of the kind had been seen by observers in the early part of the eighteenth century.

239. The annexed figure is copied from a drawing made by Mr. Dawes of the appearance of Saturn after the existence of the inner ring had been well ascertained, and, besides exhibiting the semi-reflective ring which it was principally intended to show, exhibits also a delicate sub-division of the outer ring, visible only near the extremities. It had

been previously suspected by astronomers that the outer ring had at least one sub-division, but the matter seems now by this evidence to be put beyond the reach of doubt.

The following is Mr. Lassell's description of the appearance of the dusky ring as he saw it on December 3rd, when on a visit to Mr. Dawes :—

" After surveying the planet for some time, I was struck with a remarkable phenomenon, which I shall proceed, as well as I can, to describe. It appeared as if something like a *crape veil* covered a part of the sky within the inner ring. This extended itself half-way between what I should have formerly considered the inner edge of the inner ring and the body of the planet, while there was a darker, ill-defined boundary-line separating this crape-like appearance from the solid body of the inner ring. There was an exceedingly thin line, or shadow, running along the southern edge of the northern portion of the ring where it crossed the planet, and the line seemed somewhat broader at each end, where it touched the limbs of the planet. Mr. Dawes had previously

* See *Notices of the Royal Astronomical Society*, vol. xi. p. 21.

drawn my attention to the appearance of this line before scrutinising the planet."

240. Saturn is now known to be attended by eight satellites, to which have been given the mythological names Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus. These satellites were all of them seen at the same time by Mr. Lassell, on the evening of November 21, 1850,* with his reflecting telescope, but opportunities seldom occur, and several of them require not only telescopes of great power, but a very favourable state of the atmosphere to render them visible. Of the above, the outermost, Iapetus, was discovered by Dominic Cassini, in 1671. Its distance from the planet is nearly three times as great as that of any of the others, and its orbit is considerably inclined to the plane of the ring (by 12°). It is also remarkable for the diminution of its light in certain parts of its orbit, and this obscuration occurring constantly on the same side of Saturn as seen from the earth, it is proved with tolerable certainty that it revolves on its axis in the precise time of its revolution round Saturn. Hyperion, the next satellite, reckoning inwards towards the planet, was discovered in the month of September, 1848, almost simultaneously by the Bonds at Cambridge Observatory, Massachusetts, and by Mr. Lassell at his observatory at Starfield, near Liverpool, and affords another good instance of the rivalry existing between the eminent observers of the present time.

241. Titan is the largest and best known of the satellites, and was naturally the first discovered. It was first seen by the celebrated Huyghens in 1655, March 25, and is supposed to be not much inferior in size to the planet Mars.

242. The remaining satellites are much more difficult to observe, especially the two innermost, which just skirt the ring, and at the epoch of their discovery in 1789, by Sir William Herschel, they were seen to thread like beads the almost indefinitely thin fibre of light to which the ring was then reduced.†

243. It is proper to mention that the well-devised mythological designations of the satellites are due to Sir J. Herschel, and were proposed for the purpose of avoiding the confusion arising from the order of discovery not coinciding with the order of distance, so that the numerical nomenclature, like

* See *Notices of the Royal Astronomical Society*, vol. xi. p. 19.

† See "Outlines of Astronomy," p. 336.

that employed for the satellites of Jupiter, was quite insufficient to distinguish them.*

244. Having thus discussed, as fully as our space permits, the particulars relating to the ring and satellites of Saturn, we will now give in few words the most important facts relating to the planet itself. The shape is elliptical, with an ellipticity of about $\frac{1}{9}$, as is proved by measures made by the author of this little work at the Royal Observatory, during the time of disappearance of the ring in 1848,† and essentially confirmed by measures made at Oxford in 1862. It was thought by Sir William Herschel, and the opinion, till recently, had been generally entertained by astronomers since his time, that the shape of the planet was oblong, but not elliptical, something like a parallelogram with the corners rounded off. It has, however, been proved by the above measures, confirming those made several years since by Bessel, that such is not the case, but that the shape is that of an exact spheroid of revolution of considerable ellipticity.

245. The inclination of the orbit of Saturn is 2° 30′ nearly, and the excentricity 0·0560; the mass is 94 times that of the earth, the diameter is 70,500 miles, and the force of gravity at the surface is about 1$\frac{1}{4}$ time that at the surface of the earth. The sidereal period is 10759·24 days. The diameter of the outer edge of the interior ring is about 2$\frac{1}{4}$ times that of the equatorial diameter of the body.

We will conclude this account of Saturn by an eloquent passage from Sir J. Herschel's book, to which we have so frequently had occasion to refer.

"The rings of Saturn must present a magnificent spectacle from the regions of the planet which lie above their enlightened sides, as vast arches spanning the sky from horizon to horizon, and holding an almost invariable position among the stars. On the other hand, in the regions beneath the dark side, a solar eclipse of fifteen years in duration, under their shadow, must afford (to our ideas) an inhospitable asylum to animated beings, ill compensated by the faint light of the satellites. But we shall do wrong to judge of the fitness or unfitness of their condition from what we see

* See Sir J. Herschel's "Results of Astronomical Observations made at the Cape of Good Hope," p. 415, published in 1847, where the nomenclature now in use was first proposed. In the foot-note the following remarkable passage occurs: "Should an eighth satellite exist, the confusion of the old nomenclature will become quite intolerable."

† See *Memoirs of the Royal Astronomical Society*, vol. xviii.

around us, when, perhaps, the very combinations which convey to our minds only images of horror, may be, in reality, theatres of the most striking displays of beneficent contrivance."

246. The planet URANUS was discovered by Sir William Herschel, on March 13, 1781, in the course of a general review of the heavens, being detected by its disk under a high magnifying power. At the author's request, Professor Challis obligingly measured the planet some years ago, with a double-image micrometer attached to the telescope of the great Northumberland telescope, for the purpose chiefly of discovering whether it had any sensible ellipticity, which the author suspected from some measures of his own made with a far inferior telescope. The result was that the ellipticity is too small to be measurable, and the apparent diameter about 4″. Its real diameter is about 35,000 miles.

247. The inclination of its orbit to the ecliptic is very small, being only 46½′, and the eccentricity only 0·0467. The sidereal period is 30688·39 days, or somewhat more than eighty-four of our years.

248. The satellites of Uranus, as might be expected, are exceedingly faint objects, and difficult to be observed even with very powerful telescopes; and there exist still considerable doubts respecting their orbits, and even respecting their number. Sir William Herschel observed two satellites, which are considerably brighter than the rest, about six years after the discovery of the planet, and obtained with tolerable accuracy their distances and periodic times. Several years afterwards he announced the discovery of four other satellites in the *Philosophical Transactions* for 1798, and, in a memoir printed in the *Philosophical Transactions* for 1815, he gave the results of his observations to that date. Of the six satellites thus presumed to exist, the comparatively brighter ones he reckoned to be the second and fourth, counting outwards from the planet, and their periods he calculated to be about $8^d\ 16^h\ 56^m$ and $13^d\ 11^h\ 9^m$. The periods of the others, according to his estimations, were approximately $5^d\ 21^h$, $10^d\ 23^h$, $38^d\ 2^h$, and $107^d\ 17^h$. Now, since the time of Sir William Herschel, the positions of *none* of the four satellites last mentioned have been verified, and Sir John Herschel, who bestowed considerable attention on the system of Uranus, did not succeed in seeing them, although he repeatedly observed the other two brighter ones.

The first addition to our knowledge was made at the close of the year 1847, by Mr. Lassell and M. Otto Struve, the former by means of his reflecting telescope, and the latter by means of the large refractor of the Pulkova Observatory. In the *Notice of the Royal Astronomical Society* for 1848, January 14, is a communication from each of these astronomers, announcing the discovery of at least one satellite additional to the second and fourth of Sir W. Herschel. Mr. Lassel, observed on several nights a satellite evidently nearer the planet than these, and on one occasion he observed another. The positions of both the objects observed by him were always on the north side of Uranus. M. Otto Struve observed, on the contrary, an object always on the south side of the planet, and there was only one day of observation common to himself and Mr. Lassell. These observations were very elaborately discussed, but it was not possible to arrive at any decided conclusion with regard to the orbits and periods of the presumed new satellites. But towards the end of the year 1851 Mr. Lassell was able to announce positively the existence of two satellites, whose periods, by observations which admit of no doubt, are about $2^d\ 12^h$ and $4^d\ 3^h$. The general conclusion then is that Sir William Herschel only discovered two satellites, the observations from which he thought he had detected four more, having been afterwards shown to be in fact observations of small stars in the vicinity of the planet; and that two more have subsequently been discovered by Mr. Lassell, the orbits of which are interior to those of Herschel's. The two discovered by the latter in 1787 have been named Titania and Oberon; whilst those discovered by Mr. Lassell more than sixty years afterwards are called Ariel and Umbriel. The most recent discussion of the orbits of the satellites is by Prof. Newcomb, and is contained in an appendix to the "Washington Observations" for 1873, founded upon observations made with the 26-inch equatorial of the United States Naval Observatory. That astronomer finds the periods of Ariel, Umbriel, Titania, and Oberon respectively to be $2^d{\cdot}52$, $4^d{\cdot}14$, $8^d{\cdot}71$, and $13^d{\cdot}46$.

The satellites move in orbits very different from those of all the other planetary systems hitherto treated of, the planes being nearly perpendicular to the ecliptic, and their motions in their orbits being retrograde.

249. The mass of Uranus has always been a subject of great interest with astronomers, and is now of much greater

on account of its action on the newly discovered planet Neptune. This element is of very difficult determination by means of the revolutions of the satellites, owing to their faintness. The most recent determination is that made in 1878 by Prof. Newcomb, which gives for the mass $\frac{1}{22738}$ part of that of the sun, or rather more than twenty times that of the earth. Hence the force of gravity at his surface is rather greater than that at the surface of the earth.

250. The last, and from the circumstances attending its discovery, the most interesting planet which we have to mention, is Neptune. The discovery is equally due to two mathematicians, viz. the late M. Le Verrier of Paris, and Mr. (now Prof.) Adams of our own University of Cambridge.

It had long been known to astronomers that the observed place of the planet Uranus disagreed with its place calculated from the well-known elements of its orbit by a very large quantity, and that this disagreement was increasing from year to year. At the present time, for example, the R. A. calculated in the ordinary way from the elements differs from the observed R. A. by more than 16^s, an amount of difference far exceeding any error in the calculation of its disturbances arising from the known planets, or from any failure in the theory of its motion generally. The idea of disturbances arising from some *unknown exterior planet* had been suggested long before the error attained this amount, and was the most probable solution, but some distinguished astronomers, in their uncertainty about the cause, began seriously to question the *exact* accuracy of the law of gravitation, that is, of bodies mutually attracting each other according to the inverse square of the distance. At all events, no one had courage to attack the problem under this point of view, and to endeavour to find the intruder and the disturber of our system. It appears, however, from a memorandum in the journal of Professor Adams, that he had for some years formed the resolution of endeavouring to solve the problem analytically as soon as he should get leisure from his academical engagements. Le Verrier had also been engaged in a laborious investigation of the elements of Uranus according to the existing theory, and had succeeded in finding one or two trifling additional terms of perturbations from known planets, and in discovering some inaccuracies in Bouvard's tables. He had, however, found nothing that would at all explain the enormous difference existing between theory and observation. The two *geometers* became thus, quite independently and without any

knowledge of each other either personally or otherwise, engaged in the laborious problem till then quite despaired of, of finding *the elements of a disturbing planet by means of the disturbances produced upon the disturbed planet.* The direct problem is difficult enough to try ordinary industry and patience, but the intricacies of the inverse problem were enough to make the boldest analyst and computer shudder.

We cannot give any adequate idea of the labour and difficulty actually encountered, except by stating that all the elements of the sought planet (except the mean distance which it was necessary to assume arbitrarily) must come into the equations of condition, as well as all those of the disturbed planet, or rather their corrections, since the latter elements obtained from the ordinary theory must be necessarily false. Both mathematicians did, however, arrive at about the same time at a complete relation, and both, in the autumn of the year 1846, furnished elements of the planet sought for. Le Verrier, from his elements, calculated a place of the planet, and so confident was he in the accuracy and certainty of his result, that he wrote to his friend Dr. Galle, of the Royal Observatory of Berlin, requesting him, on the night of the receipt of the letter, to direct the telescope of the large equatorial of that establishment to the indicated spot in the heavens, and giving him full assurance of finding the planet. This letter reached Dr. Galle in 1846, September 23rd. On searching as directed, he found a star of about the eighth magnitude, not marked in Bremiker's star chart (the one for that part of the heavens had just come to hand), which, therefore, afforded strong presumption of being the body sought for, and the fact was confirmed by the first night's reobservation. In the meantime, the researches at Cambridge had proved in the English mathematician and astronomer an equal degree of merit, though of course the glory of the first discovery indisputably belongs to Le Verrier and Galle. Prof. Challis, who was then Director of the fine Observatory at that University, had for some time been engaged in a laborious and well-arranged sweep of that part of the heavens which Adams's researches had pointed out as the most likely, and it is a curious fact that, before its actual discovery and recognition at Berlin, it had been twice observed by that unwearied astronomer. To explain the fact of its being observed, and yet not recognised, it is necessary to remind the reader that at this time, that section of Bremiker's star

charts which included the portion of the heavens in question, had not yet reached England, so that Professor Challis had, in fact, to *construct one for himself* from the data afforded by his observations. If the result of each night's sweep had been pricked off on prepared maps immediately afterwards, the glory of the discovery would have rested with him and Adams, but the other laborious duties of the observatory prevented this being done, at the same time that the necessity of doing it was not so obvious before the discovery as it appeared afterwards.

The claims of the rival astronomers and mathematicians are evidently, on the whole, equal, and the planet would infallibly have been discovered during the autumn by each independently. At the same time the peculiar fame arising from the happy union of transcendent analytical skill and undoubted confidence in the result must be conceded to Le Verrier; his whole process was happily conceived, carried out in the most masterly way, and immediately rewarded by his singular boldness in announcing his result and pledging his reputation on its certainty.

We could not pass by this wonderful discovery of the planet Neptune without thus much of notice. It exhibits, in the most striking way, the advance of astronomy in its theoretical development, and in its practical adaptation:—the mathematician, the observer, and the instrument-maker were almost equally needed in the solution of the great problem before us;—and if any one of these conditions had been wanting, Neptune might have remained still unknown.

251. Immediately after the discovery, the observations of the last century were ransacked to endeavour to find whether Neptune had been observed without knowledge of its planetary character, since this was of very great importance in the calculation of its real orbit from observation. The published observations of the French astronomer Lalande afforded no trace of such an observation, but, on consulting the manuscripts of these observations kept at the Observatory of Paris, two were found, made in the year 1795, on the 8th and 10th of May, which were suppressed in the printing, on account of the error presumed from their disagreement (the object being supposed to be a star), but which were really observations of the planet.

252. These earlier observations have been of the greatest possible value for determining, by combining them with *those made since* the discovery, the elements of the planet's

orbit. According to Prof. Newcomb, of the United States' Naval Observatory, Washington, the sidereal period is 164·78 tropical years, the excentricity 0·00899, and the inclination 1° 47′.

253. Soon after the discovery the planet was attentively watched by Mr. Lassell, M. Otto Struve, Mr. Bond, U. S., and by Professor Challis, for the discovery of any physical peculiarities that might be rendered visible in the powerful telescopes at their command. Mr. Lassell was rewarded by the discovery, in October, 1846, of a satellite, the orbit of which M. Otto Struve, by subsequent observations, found to be inclined to the ecliptic at an angle of about 35°. Its periodic time is about $5^d\ 21^h$, and its motion is retrograde, like those of the satellites of Uranus. It is a difficult object to see, even in the most powerful telescopes.

254. The mass of the planet has been determined both by the observations of the satellite, and by the perturbations produced upon Uranus, the existence of which perturbations, it will be remembered, first led to the discovery of Neptune. The value most recently found by the former method was determined by Professor Newcomb, and amounts to $\frac{1}{19380}$.

255. We will conclude this chapter with a few words about comets, a class of bodies allied in some respects to the planets, but differing so much in many important particulars as to make it necessary to treat of them separately.

256. Comets, like planets, revolve round the sun evidently under the influence of the law of gravitation, for they all describe orbits identical with one of the conic sections, and they all obey Kepler's "Second Law" of the equal description of areas, as is evident from the accomplished predictions of the return of some of them, for which the calculations assumed the law.

The planets, however, all describe ellipses of very small excentricity; in every case they move according to the order of the signs or with direct motion, and the inclinations of the orbits of all the principal ones to the ecliptic are small.

Comets, on the contrary, move in *parabolic* and even in *hyperbolic*, as well as in *elliptic* orbits; the inclinations of the orbits have all degrees of magnitude; and their motions in their orbit are as often retrograde as direct. Indeed, the greater number of those whose orbits have been calculated

describe parabolas having the sun in the focus; that is, during the time of their visibility, the orbit, if it differs at all from a parabola, differs so slightly, that the difference cannot be detected by observation.* Very few of them have been ascertained to move in *hyperbolas*, but the fact is certain for some of them. A great many periodical comets, however (that is, comets that circulate round the sun, and are observed, after their departure, to return to it again), moving in ellipses of various excentricities, are known at present.

257. Now our readers will remember in our remarks on the planetary motions, that a body might describe either an ellipse, a parabola, or an hyperbola round the same centre of force, the particular orbit being determined by the velocity and the angle of direction made with the radius vector at any point. Thus, supposing a body moving in a parabola suddenly to suffer some resistance which would materially lessen its velocity, it might describe an ellipse, and if its velocity were suddenly increased it would describe an hyperbola.

It is found also by telescopic observations, and by the very small effect produced on the motions of the planets when comets approach near them, as also by the very great disturbances which the motions of the latter suffer on such occasions, that the masses of all the known cometary bodies are exceedingly small; indeed, of incomparably less density than our atmosphere, or even of any of the lighter gases that we are acquainted with. Thus the comet of 1770, called Lexell's comet, actually approached, in 1779, Jupiter, within a distance scarcely exceeding $\frac{1}{500}$ part of the distance of that body from the sun, and yet produced no perceptible disturbance on the satellites, though it is exceedingly probable that its own return to visibility by us was quite prevented by the great disturbances it experienced. Again, the texture of which even the head or densest part of a comet is composed is of so small a density that the faintest stars are seen through it, though a slight fog or vapour near the earth's surface will render invisible stars of the first magnitude.

Hence we can conceive, without any undue speculation on the nature or origin of these mysterious bodies, that, whatever were the original orbit in which a comet may have been moving, a near approach to any of the large planets might so effectually change its orbit, that, before its discovery,

* Our readers are assumed to know that an ellipse, when its major *axis becomes infinite*, degenerates into a parabola.

it might be moving in any one of the curves above mentioned.

258. We have mentioned above that comets are of extreme tenuity, but we will add a few more remarks on their physical appearance, which is extremely different in different specimens of these bodies, and even at successive returns of the same. Some have been seen of immense magnitude and brightness, visible even at noon-day, and attended by a tail extending over 60° to 70° of the heavens. Generally in such cases the head consists of a brightish spot near the centre or *nucleus*, surrounded by a small circular nebulous mass or *coma;* beyond this is a small interval of clear space, and outermost of all is a luminous *envelope*, going round the coma like the head of a parabola, and generally extending in the direction of straight lines, so as to form two streams of light diverging for some distance, and sometimes reuniting. Frequently, however, the comet has no *tail* or train, and consists of a

small nebulous mass with or without a nucleus, and frequently, in the cases of what are called telescopic comets, a small nebula of extreme faintness is all that is visible to experienced eyes. Again, of comets which have tails, the shape is exceedingly various. Some have one tail, others two or three at different angles, and some have been seen with still more. Generally the tail is curved towards the part of the heavens from which the comet has been moving, but its length and the general appearance of the comet are greatly affected during the time of approach to, and recess

from, the perihelion passage, or passage through the point of its orbit nearest to the sun.

259. We will now particularise a few of the most remarkable comets that are known or suspected to be periodical.

260. Of comets of long period, the most remarkable is that known by the name of Halley's, from the circumstance of that illustrious geometer having predicted the return. On applying the principles of the theory taught by Newton with regard to these bodies, and calculating the orbits of several ancient comets, Halley found a remarkable coincidence in the elements of the orbits of comets which had appeared and been observed at nearly equal intervals of time in 1531, 1607, 1682, the latter appearance taking place in his own time. After mature consideration he alleged that these comets must be identical, and predicted the return about the year 1759. Clairaut, an eminent mathematician, undertook the calculation of the disturbances it would experience from the large planets, by which its return was delayed about six hundred days, and the comet returned again to perihelion according to prediction in the spring of 1759. It appeared once more in the autumn of 1835, when its return had been calculated with great accuracy by several eminent mathematicians.

261. Several other comets have been calculated to revolve round the sun in about the same period as Halley's; but none of these are certainly known to have been seen at more than one return. The most interesting of them at the present time is one which was discovered by Pons at Marseilles, on the 20th of July, 1812. It was observed for about ten weeks, and being found to move in an elliptic orbit with period of about seventy and a half years, it will probably return again to perihelion in the course of next year (1883.)

262. It will be, perhaps, expected that we shall say something about comets for which much longer periods have been assigned. But, however appropriate this may be to a book which professedly treats of descriptive astronomy, it involves points too uncertain for our short space on that part of the subject. It is well known that Halley thought that the comet (commonly called Newton's, because in reference to it Newton first applied his law of gravitation to comets), which made such a brilliant appearance in 1680 to himself and his contemporaries, was identical with comets seen in A.D. 1106, A.D. 531, and B.C. 45 (after the death of Julius *Cæsar*). *Gibbon* devotes a long article in the "Decline and

Fall" to the supposed successive appearances of this comet, *à propos* of what he calls its fifth recorded return in the reign of Justinian, and finishes by surmising that "at the eighth return, in the year 2355, the calculations of Bernouilli, Newton, and Halley may perhaps be verified by the astronomers of some future capital in the Siberian or American wilderness." But it is now scarcely open to doubt that the period of the comet of 1680 amounts to, not hundreds, but thousands of years; and it is probable that Justinian's comet of A.D. 531, was in fact a return of the comet ordinarily known as Halley's, of which we have spoken above. A comet which appeared about the time of the abdication of the Emperor Charles V. has been surmised to have a period of about three hundred years, and was partly expected to be seen again about 1860; it, however, failed to put in an appearance, and the moral is that too little reliance can be placed upon observations made some centuries ago to found with confidence any conclusion upon them with regard to the elements of the orbits of comets seen. Moreover, comets of very long elliptic orbits are seen for so fractional a portion of their whole period that it is impossible with a few even good observations to determine the length of these with accuracy.

263. We pass on therefore to comets of short period. Of these by far the most interesting is that commonly known as Encke's (from that astronomer having been the first, at its appearance in 1818-19, to calculate its orbit and predict its return), the period of which is the shortest of all, and amounts to little more than three years and a quarter, It appears that it was first discovered by Méchain, at Paris, in 1786, and afterwards re-discovered by Miss Caroline Herschel in 1795. At the return in 1818 it was again independently discovered by Pons, on the 26th of November, about four weeks before it passed its perihelion on the 27th of January, 1819. Now it was that Encke took it in hand, showed that its orbit was a small ellipse, that it had been seen on previous occasions, each time being supposed to be a new comet, and predicted that it would return to perihelion in the month of May, 1822, as it accordingly did. It has been seen at every subsequent return, and has occasionally been just visible to the naked eye. The exact period is 1,210 days; it was in perihelion in November, 1881, and will be again in March, 1885. A very remarkable fact was first noticed by Encke with regard to it, which later observations

have confirmed. Its periods of revolution are becoming successively shorter, and the major axis of the elliptic orbit is slowly but steadily diminishing.

264. The next most interesting comet is or rather was that known as Biela's, which, after separating into two portions in the winter of 1845 and returning as two companion comets in the autumn of 1852, would seem afterwards to have dispersed altogether, as it has not since been seen. It was first discovered so long ago as 1772, by Montaigne, rediscovered by Pons in 1805, and again by Biela in 1826, when it was shown to have a period of somewhat more than six and a half years.

265. Faye's comet has established itself as a regular member of the solar system. It was first discovered by M. Faye at Paris in November, 1843, found to have a period of about seven and a half years, and has been observed at every subsequent return, the last time about the end of 1880, the perihelion passage taking place in January, 1881.

266. M. Tempel, formerly of Marseilles, now Director of the Observatory at Arcetri, near Florence, has been the most successful modern discoverer of comets. Besides several others, he has discovered three of short period; one in 1867 (comet 2, of that year); a second in 1869 (No. 3) and a third in 1873 (No. 2), the period of each of which is between five and six years. The first returned in 1873 and 1879, the second was not seen at the next return in 1875, but was observed at the subsequent one in 1880, when it passed its perihelion on November 18th; the third, whose period is somewhat the shortest of the three, was observed in 1878, passing its perihelion on September 7th.

267. Another small comet which seems entitled to rank as a permanent member of the system, was discovered by Brorsen at Kiel in the month of February, 1846. Its period is also about five and a half years, and it was last observed in the spring of 1879.

268. A large number of new comets has been discovered in recent years, of which the most remarkable are the great comets of 1858, 1861, 1862, 1874, and 1881.

The comet of 1858 (called Donati's Comet, from its discoverer, the late Italian astronomer of that name) was the finest seen since the celebrated one of 1811. It was discovered at Florence on June 2, 1858, and was then merely a faint patch as viewed with a powerful

telescope; and it was not a conspicuous object to the naked eye till near the end of September. About that time and during the month of October, its most brilliant phenomena were exhibited. Its tail was about 40° in length, and the appearance of the nucleus when examined in a telescope exhibited changes of the most interesting and instructive character. After its perihelion passage, and being lost for a time, it became again observable, and continued to be observed till about the middle of the next year, 1859.

269. The great comet of 1861 burst suddenly upon the sight on the evening of June 30, near the north-west horizon for these latitudes. Its nucleus to the naked eye appeared almost as large as the moon, and its tail was estimated as more than 100° in length. It continued observable for two or three months.

The great comet of 1862 exhibited several interesting phenomena, but its appearance, as viewed by the naked eye, was not so grand as that of either of the preceding comets.

The comet of 1874 was visible to the naked eye for several weeks in the summer; and in 1881, as all may remember, two were at one time visible to the naked eye at once.

270. A most remarkable discovery which has been made recently with regard to comets is that of the identity of the orbits of two of them with those of the August and November swarms of meteors. Most of our readers will remember the brilliant spectacle which was presented by the meteors on the night of November 13-14, 1866. Many astronomers were prepared to take all the advantage possible of the predicted return of these meteors after an interval of thirty-three years, and by their observations, the elements of the orbit of the group were determined with considerable accuracy, and were found to coincide very precisely with those of the first comet of 1866, discovered by M. Tempel at Marseilles. On further investigations it was then found that the elements of the great comet of 1862, previously mentioned, coincided with those of the August group of meteors, and the inference naturally is that comets are in general nothing more than a collection of those meteors seen at such a great distance that the discrete particles of which they are composed present the appearance of a gaseous body, varying in form and brightness according to its changes of position relatively to the earth. The subject is, however, at present still obscure and difficult, but the facts already known suggest a wide field of inquiry and profitable investigation.

CHAPTER VII.

THE FIXED STARS.

271. Having treated of the motions of the bodies of the solar system, viz., of those bodies that describe orbits referred to that body as a centre, we have now to speak of the stars, or of those comparatively fixed bodies that preserve sensibly from one age to another the same relative situation in the heavens, and are, therefore, popularly called fixed. In the sequel we shall find that this term is not strictly true, and that the greater number of the fixed stars have measurable motions of their own, but the designation is sufficiently accurate for ordinary purposes, and serves effectually to distinguish them from the planets, whose motions, as seen from the earth, are incomparably more rapid.

272. The stars are so distant from us that they are incapable of being distinguished except by their brightness, or, to use the term generally applied, by their magnitudes. The separation of stars by magnitudes has been made from the earliest times altogether by estimation of their brightness with the eye, and this estimation being necessarily vague, the magnitudes as given in catalogues of stars are in some respects vague and indeterminate, and hardly accurate enough for the present purposes of sidereal astronomy.

273. A few stars of the heavens, pre-eminently bright, are called stars of the first magnitude, but this class includes very few, the number given in the "Nautical Almanac" list being only thirteen. Stars next to these in brightness, and differing only slightly, are said to be of the first-second or the second-first magnitude, accordingly as they by estimation appear to be nearer stars of the first or the second magnitude. The next class comprises stars of the second magnitude with its subdivisions, and so on to the third, fourth, &c., magnitudes.

The lowest class visible to the naked eye consists of stars between the fifth and sixth magnitudes, though on very clear evenings good eyes may distinguish stars of the sixth magnitude. The classes of inferior magnitudes are estimated according to their relative brightness as seen in telescopes, and of course the estimations become still more vague on account of the different powers of the telescopes employed, and because a general view of them cannot be obtained for the purpose of direct comparison, as is the case with the naked eye when directed to the heavens.

274. We are indebted to the late Professor Argelander, formerly Director of the Observatory at Bonn, for a complete classification of all the stars visible to the naked eye in the northern heavens according to their magnitudes, in a catalogue entitled "Uranometria Nova," published several years ago, which should be in the hands of every astronomical student.

275. Mr. Johnson, formerly Director of the Radcliffe Observatory at Oxford, also paid great attention to this subject, and repeatedly estimated the magnitudes of all the stars observed by him, so as to obtain a much more definite scale than has been ever practicable before.*

276. For the better classification of the stars, the ancients divided them into fanciful groups, called constellations. The boundaries of these constellations were assigned from the supposed resemblance to the figures of men, animals, &c., and in many instances represent the deified heroes or heroines of antiquity, such as *Hercules*, *Perseus*, *Andromeda*, *Cassiopeia*. The most remarkable northern constellations called by the names of animals are *Ursa Major*, *Ursa Minor*, *Draco*, *Cygnus*, *Serpens*, *Aries*, &c., together with those crossing the zodiac, as *Aries*, *Taurus*, *Leo*, &c. The number of constellations thus named, which are included in Ptolemy's catalogue, is forty-eight. Some stars of conspicuous brightness still retain the designations given to them by the Greek and Arabian astronomers, such as *Algenib*, *Achernar*, *Sirius*, *Rigel*, *Aldebaran*, *Capella*, *Arcturus*, *Antares*, *Spica Virginis*, *Regulus*, *Canopus*, *Fomalhaut*, &c. Bayer, an astronomer of the seventeenth century, the better to distinguish the stars in their respective constellations, assigned to them letters of the Greek, Italic, and Roman alphabets: the brightest star having affixed to it α, the first letter of the Greek alphabet, the second β, and so on, till, these being

* On this subject see a valuable paper by Mr. Dawes in the *Notices of the Royal Astronomical Society*, vol. xi., p. 187.

exhausted, recourse was had to Italic and Roman letters. Thus *a Aquilæ*, *a Lyræ*, are the brightest stars in the constellations *Aquila* and *Lyra* respectively.

So fanciful is this resemblance of star-groups or constellations to the forms of animals and other figures that inconvenience often results from the existing distribution, particularly when, as in several cases, the boundary of one constellation overlaps that of another. Nevertheless, the stars have become by long usage so inseparably identified with their names according to this system, that it would now be extremely difficult, if not impossible, to make a complete revision of nomenclature. All, however, who are interested in the subject are recommended to read a valuable article by Sir John Herschel, forming part of the Introduction to the Catalogue of 8,377 stars, published by the British Association in 1845.

277. We have already spoken of catalogues of stars, and it will be necessary to devote a few words to the explanation of their construction.

278. It has been explained that the places of objects in the heavens can be freed from all the effects of displacement to which the observations of them at the surface of the earth are liable, and can be referred to a fixed equinox and equator. It is usual in fixed observatories to reduce the observations of all stars to their mean positions for the beginning of the year of observation by the application of the corrections for precession, nutation, aberration, &c., and their places are then such as they would be if referred to the *mean position of the equinox and equator* for the beginning of the year; that is, the places of reference are thus fixed, and the observed places of the stars should be theoretically the same for every observation. By collecting the separate observations of each star, therefore, a mean of the results will give with considerable accuracy the mean place for the beginning of the year. The mean right ascensions and polar distances of the stars are thus collected into a catalogue according to the order of their right ascensions (that is, starting from 0^h according to the order of their diurnal revolution), and thus a catalogue of mean places of the stars observed during the year is formed. It is usual also to add in separate columns the star's mean precessional motion in right ascension and North Polar distance for one year, and, if it is known, the proper motion is also given. By these means it is easy to combine the results of several years' observations

into one catalogue for some intermediate epoch, with no greater risk of error than is entailed by the mean effect of the trifling uncertainty of the actual motion of the equinox and of the proper motion in this interval, which, for a few years, is exceedingly small in the present state of astronomy. Thus the results of all the star observations made at Greenwich, between the years 1836 and 1876, both inclusive, are embodied in six catalogues, each containing the observations for six, seven, or nine years. It was not thought prudent to combine them all into one catalogue on account of the objection arising from the possible uncertainties already spoken of, and the reader may hence judge of the jealous caution exercised in all matters subject to the smallest doubt. The proper motions of all such stars in the above catalogues as had been observed by Bradley, for the three first of the catalogues above mentioned, were computed by the author of this treatise, and Mr. Stone, who succeeded him at Greenwich, computed those for the fourth. For all these stars, then, the places can be predicted with great accuracy for at least a century, certainly with smaller risk of error than belongs to a single observation.

279. Having thus explained the formation of a catalogue of stars, we will mention some of the most important collections, both ancient and modern. The earliest forms part of the famous "Almagest" of Ptolemy, supposed to have been compiled from the observations of Hipparchus made 267 years before, and reduced to Ptolemy's epoch by adding the amount of the precessional motion in longitude. This is the only ancient catalogue, and it contains 1,022 stars.

280. The next in order is the catalogue of Ulugh Beigh, a Tatar prince, containing 1,017 stars, compiled from his observations made about the year 1437; and the next is the catalogue of the cebebrated Tycho Brahe, containing 777 stars, arranged in 45 constellations, from observations made in the latter part of the sixteenth century.

281. The above catalogues have been re-edited and rendered more available for modern readers by the late Mr. Baily, and are contained in the thirteenth volume of the Memoirs of the Royal Astronomical Society.

282. Bayer's catalogue, containing 1,762 stars, arranged in 72 constellations, we have before had occasion to notice. It was published in his "Uranometria" in 1603. Bayer introduced the classification of the stars by the letters of the alphabet.

283. The celebrated catalogue of Hevelius comes next, and contains 1,888 stars derived from his own observations. The epoch is 1661. It was published in the "Prodromus Astronomiæ" in 1690, and is the last collection of star places derived from observations made without the help of the telescope. It is included in Mr. Baily's collection before mentioned.

284. Next follows the far more important catalogue of Flamsteed, which is the real basis of correct modern astronomy. This catalogue was compiled from Flamsteed's observations made with the use of the telescope on a fixed mural arc, and was published by Flamsteed's executors in the "Historia Cœlestis Britannica" in the year 1725. It was re-edited by Baily in 1835.

285. The most celebrated catalogue of the eighteenth century is that of Bradley, containing 3,222 stars. It is included in the "Fundamenta Astronomiæ" of the illustrious Bessel, published in 1818. This book is the greatest treasure possessed by astronomers, both from the goodness of the observations on which the catalogue is founded, and for the methods of reduction used by Bessel, which comprise all the refinements of modern mathematical skill.

286. Other fundamental catalogues are those of Piazzi and Groombridge. The former contains nearly 7,000 stars, and the latter 4,243, and the respective epochs are 1800 and 1810. Both these catalogues are of inestimable value.

287. The last original catalogues which we shall mention are those of Lalande and Lacaille, containing respectively 47,390 and 9,766 stars for the years 1800 and 1750. Both these catalogues have been recently published by the British Association, the reductions of the observations having been made under the authority and at the expense of that body.

288. The best modern *compiled* catalogue (that is, a compilation from all the best *original* catalogues before mentioned) is that of the British Association, containing 8,377 stars, reduced with great accuracy, and giving the elements of reduction for obtaining the apparent place of a star for any given day. This catalogue replaced the "Astronomical Society's Catalogue," which was published in 1827, and compiled by Mr. Baily. The appearance of this latter catalogue, with Mr. Baily's elaborate preface, of itself marked a new epoch in astronomy.

289. In connection with the formation of catalogues of stars we are naturally led to treat of their proper motions.

Imagine two catalogues of the same stars to be formed for two epochs, differing by a considerable interval; for example, the star catalogue included in Bessel's "Fundamenta" (deduced from Bradley's observations), of which the epoch is 1755, and the Greenwich Catalogue of 2,156 stars, with mean epoch about 1842. Now we can, by the theory of precession which has been previously explained, bring up the places of Bradley's stars to the epoch of the modern Greenwich Catalogue without material error, and then, neglecting error of observation, which in the mean of several is very small, the result should be identical with the results of the latter catalogue. But we find this to be absolutely the case for very few stars, and, in a great many instances, the differences are so great that it is necessary to seek for some cause totally different from those apparent displacements of all the celestial bodies that we have thus far had occasion to consider. On the whole, also, the differences follow no law of sign or magnitude dependent on the position of the stars, by which we could represent their whole amount; and we are thus justified in considering them to be *real* or *proper motions* of the stars themselves. Indeed, it is exceedingly unlikely, from what we know of the motions of the bodies of the solar system, that any one of the stars is absolutely at rest, since on that supposition it could only remain so by the total absence of any attractive force from other bodies, that is, it must be at an infinite distance from every other. The observed differences then being divided by the number of years between the two epochs will give the annual proper motions of the stars. As a general rule it is found that the brightest stars, that is, the stars of the first and second magnitudes, have the largest proper motions, but this rule has most remarkable exceptions. For instance, the two stars of 61 Cygni, whose distance has been discovered (see pp. 50, 51), and whose magnitudes are not much above the sixth, have a common annual proper motion of about $5\frac{1}{3}''$, and the star No. 1830 of Groombridge's catalogue has one still greater: μ and θ Cassiopeiæ have also large proper motions. All such stars, the reader will easily understand, are likely to be much nearer to us than those whose proper motions are insignificant, and therefore afford better hope of success in attempting to investigate their parallaxes. The parallax of Groombridge 1830 appears, however, to be exceedingly small, and the various series of observations that have been made to determine it appear to prove that it does not exceed one-tenth of a second.

290. Amongst the most interesting of the phenomena ordinarily observable in the stars is that of the periodical variation of brilliancy belonging to some of them. In the time of Tycho, a star suddenly appeared in the constellation Cassiopeia, with a lustre exceeding that of stars of the first magnitude, and rivalling Jupiter and Venus when nearest to the earth. Its brightness decreased very rapidly, and at the end of sixteen months it was no longer visible. Its colour during this time underwent considerable variations. Another star of the same kind was observed in 1604, in Ophiuchus, and all the phenomena connected with it were similar to those of the former. At the present time, owing to the constant and systematic observations of the stars, a tolerably large list of *variable* stars has been collected, and the periods of maximum and minimum brightness of some of them have been ascertained. Of these β Persei is a remarkable specimen. Its whole period of change is rather less than $2^d\ 20^h\ 49^m$, during which time it varies in brightness from the second magnitude to the fourth. It continues at its state of greatest brightness for rather more than $2\frac{1}{2}$ days, and all its changes are confined to a few hours. The phenomena connected with this star strongly confirm the idea of a dark body revolving round it, and periodically obstructing a great portion of its light. Another variable star of the short period of $5^d\ 9^h$ nearly, is δ Cephei. β Lyræ has a period of nearly 13 days, divided into two periods of greater and smaller amount of change. For a list of several other stars whose periods have been ascertained with tolerable certainty, the reader may consult Sir J. Herschel's "Outlines of Astronomy," page 558, and we would recommend the study of this interesting class of stars to any of our young readers who are provided with a telescope of moderate power, as a very delightful and profitable exercise. Mr. Hind, whose labours we have occasion so frequently to mention, has added four to the list. Such stars as those observed in the sixteenth century are more properly denominated *temporary* stars, the designation *variable* being confined to those that have a determined period of maximum and minimum brightness. For an account of a very remarkable temporary star which suddenly appeared on May 12th, 1866, the reader is referred to the Appendix to this volume.

291. Of the different hypotheses devised for the purpose of accounting for the phenomena of variable stars, the two *most probable* are that either the stars, like the sun, rotate

on an axis of revolution, and present in succession surfaces of greater and lesser illumination; or that they are attended by opaque bodies or planets revolving round them, and periodically obstructing some of their light. Bessel thought that he had discovered a variability in the proper motions of Sirius, Procyon, and one or two other stars which have been accurately observed for about a century, which could be explained by the disturbances incident to a planetary system, but his conclusions require confirmation, and some of the details will probably undergo modification.

292. The next class of stars presented to our notice are *double and multiple stars*. These may themselves be divided into two classes, viz., either those that are only *optically* double, that is, by being projected when seen from the earth on very nearly the same point of the heavens; or those which are physically connected by gravity, and revolve round each other as the planets do round the sun. The researches connected with this portion of modern astronomy owe their origin to Sir W. Herschel, to whom we are indebted for the first catalogues of double stars. Since his time it has been most zealously prosecuted by his illustrious son and Sir James South, with several other astronomers in England, but especially by the great Russian astronomer Struve. Struve's large catalogue of double stars, in connection with Sir John Herschel's observations at the Cape of Good Hope, has given us in this particular a complete survey of the northern and the southern heavens, and these eminent astronomers have left nothing for future observers but a scanty gleaning after their rich harvest.

293. The observation of a double star consists (in addition to notes of magnitude and colour) in the determination of the *distance* in seconds of arc of the two components, and of its *angle of position*, that is, of the angle which the line of direction of its components makes with the meridian, or great circle joining the pole and the stars. By observations continued through the greater part of a century, it is certain that the angle of position of several double stars is not fixed, but that the line joining the components revolves constantly in the same direction, and some stars have actually completed a whole revolution since the commencement of accurate observation. Three of the most remarkable of these physically connected systems are, 61 Cygni and γ Virginis in the northern hemisphere, and α Centauri in the southern. The distance of the two stars of 61 Cygni has been tolerably

constant since the earliest observations, and is about $15\frac{1}{2}''$; but the angle of position has varied by about $50''$ in seventy years. Now we have in our chapter on parallax shown (pp. 50, 51) how the parallax, and therefore the distance of this star from the sun, has been measured by Bessel, and we need only repeat here that the mean value of the parallax (or angle subtended by the radius of the earth's orbit at the star, or rather the value of the angle whose tangent is $\frac{\text{rad. of earth's orbit}}{\text{dist. of star}}$), is $0''{\cdot}348$. Hence it follows, that the distance between the stars is greater than the radius of the earth's orbit in the proportion of $15\frac{1}{2}$ to $0{\cdot}348$, or of $44\frac{1}{2}$ to 1 nearly. The orbit, therefore, described by these stars round each other must of necessity be considerably greater than that of Neptune, whose distance from the sun is not much greater than 30 times the radius of the earth's orbit. Again, supposing the revolution of the stars round each other to be uniform, their time of describing the complete orbit will be $\frac{360}{50} \times 70$ years, or rather greater than 500 years. By means of these data, we find, by the application of Kepler's third law, the sum of their masses to be a little greater than one-third of the mass of the sun.

294. The distance of the two components of α Centauri was in 1834 about $17\frac{1}{2}''$, and decreases at the rate of about half a second per year, while the angle of position remains tolerably constant. Observations have not been continued long enough to determine the orbit described by the stars round each other with any accuracy; but if we assume, with Sir J. Herschel, that the major axis must at the least exceed $24''$, and with Henderson and Maclear (see pp. 52, 53) that the parallax is rather less than $1''$, then the real value of the axis of the orbit described is at least 13 times that of the earth's orbit.

295. γ Virginis is another remarkable double star whose components are physically connected and of nearly equal magnitudes. This star has had the elements of its orbit calculated by several astronomers with great exactness, according to the principles laid down by Sir John Herschel. The late Admiral Smyth devoted considerable time and labour to this investigation, both by methods of ordinary calculation and by graphical methods, and it occupies a considerable space in his well-known book, "A Cycle of Celestial Objects."

296. When the components of a double star are very unequal in magnitude, their colours are generally complementary to each other; thus, if the larger star be of a yellowish colour, the lesser one will appear bluish; but if the colour of the larger star incline to crimson, the other will be of a greenish hue; if again the smaller star be very much fainter than the other, the latter will not be affected by its light. Sir J. Herschel suggests the possibility of these colours being not purely the result of contrast, but of light differently tinted, emanating from the stars themselves; and if this should be the case, it is scarcely possible to imagine the glorious effects of coloured lights that would be produced during the revolutions of the planets attendant on such primaries. In many parts of the heavens, stars of a deep red colour occur, unattended by companions, but stars of a green or bluish tint have never been observed alone.

297. It was suspected by Sir W. Herschel that the sun has a proper motion in space, and this opinion, conformable as it is with analogy, has been proved to be true, though the illustrious Bessel, from the results of Bradley's Observations, thought otherwise. In any extensive catalogue of proper motions * in right ascension, if the very small and doubtful ones be rejected, it will be found that from about seventeen hours to five hours of R. A., the proper motions are on the whole such as to increase the right ascension, and that between five hours and seventeen hours they tend to diminish them. Now this is just the effect that would be produced by the motion of the sun towards a point in the heavens of about seventeen hours R. A., for it is evident that the angular distances of all the stars in that part of the heavens towards which the sun is moving will be increased, while the angular distances in the opposite part of the heavens will be diminished. The stars will therefore be, with regard to right ascension, apparently thrown farther away from the seventeen-hour meridian, and the right ascensions greater than seventeen hours will be increased, while those less than seventeen hours will be diminished, which is conformable to the observed fact. Several elaborate investigations have been made of the position of the apex of

* See, for example, the author's discussion of the proper motions of stars of the Greenwich Catalogue by comparison with Bradley's Observations. *Memoirs of the Royal Astronomical Society*, vols. xix. and xxviii.

solar motion by Professor Argelander, M. Lundahl, M. Otto Struve, Mr. Galloway, and Sir George Airy. M. Otto Struve, by some very refined speculations, deduced not only the *direction*, but a very near probable value of the *amount*, of the solar motion. By his results, it appears that the sun is moving towards a point in the constellation Hercules, defined by R. A. 259°, and N. P. D. 55°, with an annual velocity of about 0″·3 measured in the arc of a great circle for a star at the unit of distance, situated 90° distant from the apex of motion. The much more elaborate investigation of Sir George Airy and Mr. Dunkin has shown that the amount of the solar motion is still subject to great uncertainty.

298. The late Professor Mädler, some years ago, made an elaborate attempt to determine the point of the heavens where the central body is situated, round which the sun revolves. This point he placed in the group of the Pleiades, but his view has not met with general acceptance amongst astronomers. That group is considerably out of the plane of the milky way, a situation, says Sir J. Herschel, which is "in itself very improbable, since it is almost inconceivable that any *general* circulation can take place out of the plane of the galactic circle."

299. Thus far we have treated of stars properly so called, that is, of celestial objects which, when viewed with telescopes of the highest power, present to the eye only single points of light. But there are scattered in various parts of the heavens other objects which never present the image of a star, and are seen very differently, according to the power of the telescope employed. Such objects are classed under the general term *nebulæ*. When viewed with telescopes of moderate power, such as those in use before the time of Sir William Herschel, they present generally the appearance of a small *nebulous* or *clouded* mass of light.

300. In the *Connaissance des Temps* (French Nautical Almanack) for 1784, Messier gave a catalogue of 103 nebulæ, and those contained in his catalogue have been since generally referred to under the numbers assigned by him. In general they appeared to him simple nebulous masses, and received no farther subdivision. But the powers of Sir William Herschel's large reflecting telescopes showed a great variety of structure and form of these wonderful objects, and he was enabled to resolve all that he discovered in his general sweep of the northern heavens into the following classes:—

1st. Those decidedly resolved into clusters of separate stars.

2nd. Those which were not wholly resolved, but which

apparently would be by the use of greater optical powers. 3rd. Those which in his telescopes showed no trace of resolution. 4th. Planetary nebulæ. 5th. Stellar nebulæ; and 6th. Nebulous stars.

We will devote a few words to each of these classes.

301. Of the first class a remarkable specimen is Messier 13, pictured in Sir J. Herschel's "Outlines of Astronomy." It consists of a nearly spherical mass, containing a closely-wedged multitude of stars compressed into a space not greater than 10′ in diameter, with a remarkable condensation of numbers and brightness towards the centre. Others of this class are of irregular figure, and generally contain fewer stars, and have less condensation towards the centre. They are mostly found either in or near the milky way.

302. Of the second class (many of which, imperfectly resolved before, have yielded to the powers of Lord Rosse's gigantic 6 ft. reflector), the shape is generally round or oval, the irregularities of their outlines being probably rendered invisible by the distance.

303. Of the nebulæ which are with great difficulty or not at all resolved in the most powerful telescopes, the most remarkable are the *elliptic* and the *annular*. In the elliptic the density always increases towards the centre, and the excentricities are of every magnitude, some being very flat or almost resembling a straight line, and others of very moderate ellipticity. The most remarkable nebula of this class is that near ν Andromedæ (in the girdle), visible to the naked eye, and frequently mistaken for a comet.* It was observed in America by the late Mr. G. P. Bond, formerly Director of the Observatory of Cambridge, near Boston, with the great refractor of that establishment, and some very remarkable peculiarities of its form, extent, and general structure have been elicited by his description. (See *Trans. American Acad.*, vol iii.)

304. *Annular nebulæ* are very rare, but the most remarkable specimen is in Lyra, between the stars β and γ of that constellation. It consists of an elliptic ring of well-defined nebulous light, the axes being nearly as 5 to 4. The central vacant space contains traces of nebulous matter, and Lord Rosse with the 6 ft. reflector detected a pretty bright star not far from the centre, and a few other minute stars.

* Indeed, there are probably few astronomers, as Sir John Herschel remarks, who have not had the *misfortune* once at least in their lives to make this mistake. It is exactly like a comet without a tail.

"In the annulus there are several minute stars, but there was still much nebulosity not seen as distinct stars."

805. *Planetary nebulæ* present circular or slightly oval disks, resembling planets, but with different degrees of definitions at the borders. Very few of these objects have been discovered, and of these the greater number are in the southern hemisphere. One of the largest, however, is near the star β Ursæ Majoris, following it in the same parallel by about 12^m of R. A. Its apparent diameter is about $2\frac{2}{3}'$, which would imply a real diameter seven times greater than the orbit of Neptune, even supposing it no farther from us than 61 Cygni.

806. *Double nebulæ* sometimes occur; and if, as seems very probable, they are like physically-connected double stars, that is, if they form two distinct systems of countless stars, each having its own centre of condensation, yet revolving round each other by the tie of gravitation, imagination quite fails to realise the vastness of the idea thus suggested to us.

807. *Nebulous stars*, as defined by Sir J. Herschel, consist of "a sharp and brilliant star, concentrically surrounded by a perfectly circular disk or atmosphere of faint light, in some cases dying away insensibly on all sides, in others almost suddenly terminated." 55 Andromedæ and 8 Canum Venaticorum are good specimens of this class. Lord Rosse gives a most interesting account of a star of the eighth magnitude of this class as seen with his 6 ft. reflector. "There is no trace of resolvability. The outer ring is seen on a pretty good night completely separated from the nucleus surrounding the brilliant point or star. . . . There is a small dark space to the right of the star which indicates a perforation similar to that discovered in some others." Of ι Orionis the characteristics are still more interesting.

808. Many of the nebulæ viewed by Lord Rosse are remarkable for a *spiral conformation*; that is, from a point of very great condensation nebulous streaks of variable density radiate in spiral convolutions, and in a way which denotes great regularity in the organisation of the structure. Nos. 51 and 99 of Messier, which are sketched by his lordship, are beautiful specimens. (See *Phil. Trans.* for 1850, for drawings of the nebulæ as seen by Lord Rosse.)

809. We have now given a passing notice of all the classes of nebulæ which are visible in the northern hemisphere, but there are two remarkable phenomena visible with the naked

eye in southern latitudes, called the *Magellanic Clouds*, which require mention. They are two cloudy masses of light, of a somewhat oval shape, but the larger deviates most from the circular form, and exhibits "the appearance of an axis of light, very ill defined, and by no means strongly distinguished from the general mass, which seems to open out at its extremities into somewhat oval sweeps, constituting the preceding and following portions of its circumference.... When examined through powerful telescopes, the constitution of the nebulæ is found to be of astonishing complexity. The general ground of both consists of large tracts and patches of nebulosity in every stage of resolution, from light irresolvable with 18 inches of reflecting aperture, up to perfectly separated stars like the milky way, and clustering groups sufficiently insulated and condensed to come under the designation of irregular, and in some cases pretty rich clusters. But, besides these, there are also nebulæ in abundance, both regular and irregular; globular clusters in every state of condensation; and objects of a nebulous character quite peculiar, and which have no analogy in any other part of the heavens."*

310. We have now completed the plan which was proposed at the outset of this work. Beginning with those remarkable features and phenomena of the heavens which are forced on the attention of every one alike, we have endeavoured to trace the successive steps in the reasoning by which the diurnal and apparent are separated from the real motions of the heavenly bodies. We have then given, as fully as our space permits, an account of the operations by which the figure and dimensions of our own globe are ascertained, and by which it becomes the basis for the measurement of the magnitudes and distances of the other planets. An account has then been given of those instruments principally employed for determining relatively and absolutely the positions of the heavenly bodies, and of the successive corrections which it is necessary to apply to the observed places before they can be rendered available for the use of the theoretical astronomer. A specific account is then given of the bodies of the solar system, viz., of the great centre of attraction, the sun, and of all those bodies that revolve round him in elliptical orbits, and in this part of the work we have endeavoured to introduce the reader to

* "Outlines of Astronomy," p. 613.

some popular notions respecting physical astronomy, or the effects of the universal law of gravitation in producing not only the motions which rough observations of the planets exhibit to us, but those minute deviations which only refined observations can detect and the most refined and complicated analysis can extract as consequences of the general law. Lastly, the student has been introduced to a popular view of sidereal astronomy, and to the wonders which such telescopes as Lord Rosse's have revealed to us.

If an intelligible idea has been gained of the processes and results of astronomical science thus briefly sketched,—if the student has learnt at all to appreciate the labours of those learned men who have with unwearied industry, each in his own department, helped to build up the noble structure of the theory of the heavens, such as it is exhibited to the more advanced student at present; but above all, if he has learnt to adore more profoundly the infinite wisdom of the Almighty Architect who, by his word, created all these wonders that we are lost in contemplating, this little book will not have been written in vain; and the author will not regret having added one volume more to the list of those handbooks of popular astronomy that seem even now too numerous. The study of Astronomy, to benefit the reasoning powers of the student, must show the nature of the processes by which the grander features of the science, which all delight to contemplate, have been arrived at; and must at the same time point out with some accuracy the boundaries of our knowledge. We deal with a science which abounds in the marvellous and illimitable. We gird the earth with a measuring line of indisputable accuracy, and we measure the distances and determine the weights of the planets with wonderful precision, and we finally enter within the regions of what we might have supposed infinite space, and find the distances and determine the masses of the stars. But these successive steps have been gained by no empirical processes, but by the sure yet cautious application of inductive principles. As the *quantity* on which the phenomenon we are seeking depends becomes less and less, our jealous scrutiny of all the sources of error and delusion in our instruments and means of observation becomes greater, and the analytical processes by which we extract it from our observations become more refined.

We have endeavoured to familiarise the mind of the *student* with such principles in the *first* place, and in the

second to give a sufficient number of examples of the most interesting facts and phenomena of the science. If the *principles* be understood, a multitude of books will be found which will give the *results* in a more taking and interesting form. Our aim has been not to write a merely popular, but a useful book, which may serve as an introduction, both to such books as Sir J. Herschel's "Outlines of Astronomy," which embraces the whole subject in a popular shape for one class of readers, and for another class to books which are devoted to the mathematical and systematic treatment of the subject.*

* Amongst the latter, there is none which holds a higher place than that by Mr. Main himself, "Practical and Spherical Astronomy for the use chiefly of Students in the Universities," published in 1863; nor can we omit to mention, for its clear exposition of the simpler parts of mathematical astronomy, a smaller work by his son, Mr. P. T. Main, "An Introduction to Plane Astronomy," which first appeared in 1861.—Ed.

APPENDIX.

ON SPECTRUM ANALYSIS AS APPLIED TO THE HEAVENLY BODIES.

1. No Treatise on Descriptive Astronomy could at the present time be considered complete without some account of what is called spectrum analysis. To understand the discoveries which have been made in this branch of science, the student must be assumed to have some acquaintance with physical optics; but the facts necessary to be known are so few and simple that it will be well to devote a few lines to them before proceeding to explain the discoveries which have been made by their application to the science of Astronomy.

2. Light, as we are commonly conversant with it, is pure or white; that is, the images of objects rendered visible by it are ordinarily colourless, if it passes without interruption from the object to the eye. If also it be reflected at the surface of glass, or any other polished surface, it is colourless, as in the case of an object seen in a mirror or looking-glass. If, however, the rays be *separated* by being made to pass *through* glass, or any other transparent substance, before meeting the eye, the image of an illuminated object is no longer colourless, but spread out or *dispersed* in a variety of brilliant colours. A triangular prism of glass is generally used for experiments upon this dispersion of light, and the coloured image thus dispersed is called a *spectrum*. Most persons are familiar with the spectrum thus produced by a beam of sunlight made to pass through a prism, and from thence upon the wall of a room. As, however, each point of the surface of the sun sends out a beam of light which forms a separate spectrum, considerable confusion would arise in the colours thus produced, and no scientific deductions could be made

without several preliminary precautions. As the dispersion will be produced in a plane perpendicular to the length of the prism, light is introduced into a generally darkened chamber through a very thin aperture or slit, and the prism is laid against it with its sides parallel to its direction. If, then, the eye be applied to the prism, or if the images be thrown upon the opposite wall of the room (presuming that the prism is a good one, that is, made of homogeneous glass without striæ or other defects, and with its sides accurately plane), the boundaries of the colours of the spectrum can be well observed, and even some of the more difficult phenomena, with the unaided eye; but for scientific observations it is usual to employ a small telescope furnished with a micrometer for measurement of the different portions of it.

3. The colours, as given by Newton, which will be seen in the ribbon of dispersed light thus produced, are seven, namely, red, orange, yellow, green, blue, indigo, and violet, of which the red arises from the least refrangible rays, and the violet from the most refrangible, the others having a calculable refrangibility lying between the extremes.

4. On a careful examination through the telescope, it will be found that the different colours are crossed by a great number of dark lines, not absolutely black, but of different degrees of blackness. These are called Fraunhofer's lines, from the name of the celebrated German optician who first accurately observed and measured the position of them in the year 1815, though the discovery of them was due in the first place to our own countryman, Dr. Wollaston, in the year 1802. Some of these lines are more conspicuous than others, and Fraunhofer chose eight, which he denominated A, B, C, D, E, F, G, and H, with which to compare the rest. A, B, and C are single dark lines in the red; D is a double line between the orange and the yellow; E is a group of fine lines in the green; F is a strongly-marked black line in the commencement of the blue; and G and H are two groups of fine lines in the indigo and violet respectively. It must be remarked, as important to be remembered, that these lines, when sunlight is used, are invariable in their positions relatively to the colours of the spectrum.

5. For many years these dark lines of the solar spectrum led to no further discovery, though philosophers were induced to speculate on their nature, and their guesses led gradually to a better knowledge of their origin. Thus, both Sir John Herschel and Sir David Brewster attributed them to the

absorption of some of the rays; and, in the year 1832, the latter, after passing rays produced from some incandescent body through the coloured vapour of nitrous gas, produced a vast number of interruptions resembling Fraunhofer's lines. Professor Daniell, Professor Miller of Cambridge, and others soon proved that those lines depended specifically upon the kind of vapour or gas which was employed, and afterwards Professor Wheatstone discovered that the spectra produced by incandescent vapours of several of the metals consisted of a comparatively small number of detached bright lines, separated from each other by wider intervals of darkness. He was also enabled to declare, as the result of his researches, that "by this mode of examination the metals might be distinguished from each other." Other philosophers, including M. Foucault, Professor Stokes, Professor Angstrom, and Dr. Balfour Stewart, were engaged in researches on this same subject, and were on the trace of the great discovery or generalisation which was actually reserved for a German physicist, Professor Kirchhoff.

6. The great truth enunciated by Kirchhoff, which is the basis of all the discoveries which have followed, is this: that if a vapour, rendered incandescent by being raised to a high temperature, emits rays of certain refrangibilities—that is, of various definite colours—when exhibited in the spectrum, the same vapour, when at a lower temperature, will have the property of absorbing those particular rays, or of replacing them by dark lines in the spectrum. He proved, in fact, by making a series of experiments on various gases and vapours, that when they are interposed between the eye and an incandescent body, they produce a series of dark lines in the spectrum, and that the group of dark lines produced by each vapour is identical in number and position with the group of bright or coloured lines of which the light of the vapour consists when it is luminous.

This great truth was no sooner communicated, in 1859, than it was eagerly tested by original inquirers, and by none more zealously than by our own countrymen, Mr. (now Dr.) Huggins and the late Dr. W. A. Miller.

7. The principle of the application of the law is very obvious. Take, for instance, the case of the solar spectrum. The dark lines in it are produced by relatively cold vapours intervening between the eye of the observer and the photosphere of the sun, and these vapours arise from certain *substances* in the sun of which we wish to investigate the

nature. We must plainly vaporise by heat the terrestrial substances which we wish to compare, and find out, if possible, which of the bright lines produced in the spectrum are identical in position with some of the dark lines in the solar spectrum. To do this, it is necessary that the two spectra should be examined together, or fixed in juxtaposition with each other; and in this consists the difficulty of devising a suitable apparatus.

We will describe in Dr. Huggins's own words that form of spectroscope which was devised by him for the purpose, and used for measuring the spectra of the stars.

8. "Within the tube or adapter of the telescope (equatorially mounted and driven by clockwork) another tube slides, carrying a cylindrical lens. This lens is for the purpose of elongating the round point-like image of the star into a short line of light, which is made to fall exactly within the jaws of a nearly closed slit. Behind this slit an achromatic lens, placed at the distance of its own focal length, causes the pencils to emerge parallel. They then pass into two prisms of dense flint glass. The spectrum which results from the decomposition of the light by the prisms is viewed through a small achromatic telescope. This telescope is provided with a micrometer screw, by which the lines of the spectra may be measured.

"The light of the terrestrial substances which are to be compared with the stellar spectra is admitted into the prism in the following manner:—

"Over one half of the slit is fixed a small prism, which receives the light reflected into it by a movable mirror placed above the tube. The mirror faces a clamp of ebonite provided with forceps to contain fragments of the metals employed. These metals are rendered luminous in the state of gas by the intense heat of the sparks from a very powerful induction coil. The light from the spark, reflected into the instrument by means of the mirror and the little prism, passes on to the prisms in company with that from the star.

"In the small telescope the two spectra are viewed in juxtaposition, so that the coincidence and relative positions of the bright lines in the spectrum of the spark with the dark lines in the spectrum of the star can be accurately determined."

9. It is proper now to give a short account of the nature of the discoveries which have been recently made by means of spectrum analysis, and we will commence with those made

by our distinguished countryman, Dr. W. Huggins, of Tulse Hill, who is second to none in his laborious and successful investigations in this branch of science. The best popular account of his researches, up to the year 1866, is that given by himself in his discourse at Nottingham, during the meeting of the British Association for that year, and we will give from it a notice of his discoveries in the various classes of the heavenly bodies in the same order as they are given by himself.

10. First, with regard to the *fixed stars.*

He refers particularly to his observations of some of the brightest of them, and selects six, namely, Aldebaran, α Orionis, β Pegasi, Sirius, α Lyræ, and Pollux.

In all of these he detects the presence of sodium and magnesium; in five of them, iron; and in one, barium. But the most remarkable are α Orionis and β Pegasi, not for what they contain, but for what they do not contain.

In the spectra of these stars, for instance, there is no dark line corresponding to hydrogen; and Dr. Huggins considers this as a very important and interesting fact, since the lines C and F, which are absent in these spectra, are highly characteristic of the solar spectrum, and of the spectra of by far the larger number of the fixed stars to which his observations have been extended. "We hardly venture," he says, "to suggest that the planets which may surround these suns probably resemble them in not possessing the important element, hydrogen. To what forms of life could such planets be adapted? Worlds without water! A power of imagination like that possessed by Dante would be needed to people such planets with living creatures."

11. With regard to variable stars, the prism does not appear to as yet give much positive information; but in the case of one of them, α Orionis, when at its maximus of brilliancy, on February, 1866, Dr. Huggins missed a group of dark lines, the exact position of which had been determined with great accuracy two years before.

12. With the phenomena of the variable stars may be associated temporary stars, or such as burst out at long intervals with sudden brilliancy, and then vanish again or become of their former magnitude.

Such was the star which suddenly burst out in the time of Tycho Brahe, and that which appeared in Corona on the 12th of May, 1866. Dr. Huggins, together with Dr. W. A. Miller, examined the spectrum of the latter star on the 16th

of May, when they noticed some exceedingly interesting circumstances. The spectrum was found to consist of two distinct parts, or rather there were two distinct spectra, one of which was formed of four bright lines, and the other was analogous to those of the sun and stars. Now the character of the spectra with the bright lines shows that it had its origin in incandescent gases, and the positions of two of the lines showed that one of the gases was hydrogen.

"These facts, taken in connection with the sudden outburst of the star and its rapid decline in brightness from the second to the eighth magnitude in twelve days, suggested the startling speculation that the star became suddenly wrapped in the flames of burning hydrogen."

This—if the explanation be correct, which scarcely admits of doubt—is certainly one of the grandest convulsions of nature which the eye of man has been ever permitted to see.

13. We now pass on to the nebulæ, in which Dr. Huggins has for ever set at rest the doubt whether many of them are really gaseous substances, as their names and general appearance seem to denote, or whether they are simply clusters of stars seen at too great a distance to admit of being resolved by our most powerful telescopes.

In August, 1864, Dr. Huggins first began the successful observations which have for ever settled the nature of these bodies. He first applied the spectroscope to a planetary nebula, small, but bright, which is designated in Sir W. Herschel's list as 37 H, iv. To his surprise he found, instead of the usual band of coloured light given by the stars, three isolated bright lines only. Now a spectrum of this kind, it will be seen from what has preceded, can be produced only by light which has emanated from matter in the state of gas, and therefore the long-vexed problem of the nature of the nebulæ was solved—at least with regard to that particular one. The next step was to determine the nature of the gas put in evidence by the light; and by examination of the brightest of the lines, it was found to be due to nitrogen, and it occurs in the spectrum about midway between *b* and F of the solar spectrum.

This may suffice to exemplify the processes employed by Dr. Huggins. He has continued up to the present time his researches upon the nebulæ; but, up to the year 1866, he had examined sixty of them, of which one-third were found to belong to the class of gaseous bodies. This is found to be strictly in unison with the inference to be drawn from Lord

Rosse's telescopic observations, as it is found that about half of the nebulæ which give a continuous spectrum (that is, which consist of non-gaseous bodies) have been resolved by Lord Rosse's large reflecting telescope, and about one-third more are probably resolvable; while, of the gaseous bodies (namely, those which show only bright lines in the spectrum), none have been certainly resolved.

14. Before leaving the subject of the stars and nebulæ, it is proper to mention a very important and interesting discovery of Huggins with respect to the proper motions of the stars. Considering that the colour of any particular part of the spectrum depends solely on the refrangibility of the rays which form that part, and that the index of refraction depends (according to the undulatory theory of light) upon the wave-length, or the number of vibrations made in a given time, anything which will alter the wave-length or the number of vibrations will disturb the position of the separate parts of the spectrum, and therefore of the lines of absorption (or dark lines), which have always a fixed relation to the colour. If, then, a star or other source of light be in rapid motion, it is plain that the number of vibrations which reach the eye in a given time is altered, and the position of each band or dark line in the spectrum of the star will therefore be altered; and the only question is whether the alteration of position with regard to the corresponding bright line o ithe heated metallic vapour with which it is compared is measurable.

15. Dr. Huggins has made a great many experiments upon several stars, and believes that he has been successful in assigning a tolerably correct motion to Sirius. The line which he examined successfully was the hydrogen line F, and the displacement measured indicated a motion of recession between the earth and står of 41·4 miles per second, and, subtracting from this the amount of the earth's motion from the star in the direction of the visual ray, which, by calculation for the time of the observation, amounted to about twelve miles per second, there remain 29·4 miles per second as the velocity of recession of the star.

16. We have now only to consider the discoveries which have been made with regard to comets.

In 1868, Dr. Huggins examined the periodical comet Brorsen at its return that year, and a new comet (ii. 1868) discovered by Professor Winnecke in the month of June. The spectra exhibited by both comets consisted of three bands of light. These bands, though in similar parts of the

spectrum, differed considerably in position and character. The spectrum of shaded bands of Comet II. was found, by direct comparison with that of olefiant gas, to be identical in refrangibility and in general character with the spectrum of carbon. Dr. Huggins repeated his observations several times, and satisfied himself with the true identity of position of the lines, and he believes that "the close resemblance of the spectrum of the comet to the spectrum of carbon necessarily suggests the identity of the substances by which in both cases the light was emitted."

Another comet, examined at an earlier period, namely, the beginning of 1866, exhibited in the spectroscope two spectra—a very faint continuous spectrum of the coma, showing that it was visible by reflected light, and a light point about the centre, exhibiting the spectrum of the nucleus. This latter spectrum shows that the light of the nucleus is different from that of the coma, in being self-luminous, and its position indicated that the material of the comet was similar to the matter of which the gaseous nebulæ consist.

In 1864, the late Donati, of Florence, found that the spectrum of a comet visible in that year consisted of bright lines.

17. We cannot do better, in concluding this part of the subject, than sum up the facts which have been elicited by the investigations of Dr. Huggins in his own words:—

(1.) All the brighter stars, at least, have a structure analogous to that of the sun.

(2.) The stars contain material elements common to the sun and earth.

(3.) The colours of the stars have their origin in the chemical constitution of the atmosphere which surrounds them.

(4.) The changes in brightness of some of the variable stars are attended with changes in the lines of absorption of the spectra.

(5.) The phenomena of the star in Corona appear to show that, in this object at least, great physical changes are in operation.

(6.) There exist in the heavens true nebulæ. These objects consist of luminous gas.

(7.) The material of comets is very similar to the matter of the gaseous nebulæ, and may be identical with it.

(8.) The bright points of the star-clusters may not be in all cases stars of the same order as the separate bright stars.

18. *Dr. Huggins* has, however, not altogether confined his

investigations to the stars, nebulæ, and comets. He has made many valuable observations of the surface of the sun, the moon, and the large planets. By these observations we have better information than was before possessed of the nature of the atmospheres of the planetary bodies, though it is on the whole of a negative character.

The spectra of various parts of the moon's surface, when examined under different conditions of illumination, showed no indications of an atmosphere.

In the spectrum of Jupiter lines are seen which indicate the existence of an absorptive atmosphere, but they are very few.

The spectrum of Saturn is feeble, but lines similar to those which distinguish the spectrum of Jupiter have been detected.

On one occasion some remarkable groups of lines were seen in the more refrangible part of the spectrum of Mars. These may be connected with the red colour which distinguishes the planet.

No additional lines were detected in the spectrum of Venus, affording indication of an atmosphere. This is probably owing, as in the case of some of the other planets, to the circumstance that the light is reflected, not from the planetary surface, but from clouds at some elevation above it.

19. While these interesting investigations, attended with such important discoveries, were being made by Mr. Huggins, other physicists had not been idle, and discoveries with respect to the surface of the sun had been made, of very great importance.

The two most successful investigators have been Mr. J. Norman Lockyer in England, and M. Janssen in France. Mr. Lockyer has been engaged for some years in spectroscopic examination of the sun, and the results of his investigations are given in various papers communicated to the Royal Society, and to the French Academy of Sciences. As summed up by himself, they are :—

(1.) The determination of the exact positions and number of the bright lines observed in the red flames, the phenomena which characterise them, and the substance of which they are principally composed.

(2.) The determination of the fact that the red flames are merely local heapings up of an envelope which is continuous round the sun.

(3.) The approximate determination of the pressures

existent in the prominences and at the bottom of the continuous envelope.

(4.) A discussion of the bearing of these discoveries on the received theory of the physical constitution of the sun.

20. The most remarkable discovery, however, which is to be mentioned in this department of spectroscopic investigation is that of devising means for observing the red prominences, which have been usually seen only during total eclipses round the sun's disk, at ordinary times. This discovery was made independently by Mr. Lockyer and M. Janssen, the former having the priority of idea, and the second of the actual discovery. At the close of a paper communicated to the Royal Society in 1866, Mr. Lockyer suggests that the spectroscope might be made to afford evidence of the existence of the red flames, though they escape all other methods of investigation, and, in the beginning of 1867, he made application to the administrators of the Government Grant Fund of the Royal Society for a more powerful spectroscope. The request was complied with, but the spectroscope was not completed and delivered to Mr. Lockyer till October 16, 1868. The success was complete on the first day when he began to work with it, namely, October 20, and he was enabled at once to determine that the prominences consisted of hydrogen, by the absolute coincidence of two of the bright lines with the Fraunhofer lines C and F.

21. In the meanwhile the same discovery was made by M. Janssen on the day immediately following the eclipse of August 17-18th, 1868, namely, on the morning of the 19th; and he was enabled not only to see the bright lines in the spectrum of the prominences, but to give a graphical representation of their size and shape.

M. Janssen observed at Guntoor, as has been already mentioned in a former part of this book, and his letter, containing an account of all his observations on that occasion, as well as of this discovery, was received by the French Academy a few minutes after Mr. Lockyer's communication had been handed to the president of that body.

M. Janssen sums up his investigations with regard to the red prominences as follows:—

(1.) That the luminous protuberances observed during total eclipses belong incontestably to the circumsolar regions.

(2.) That these bodies are formed of incandescent hydrogen, and that this gas predominates, if it does not form the exclusive composition of them.

(3.) That these circumsolar bodies are the seat of movements of which no terrestrial phenomena can give any idea—masses of matter, of which the volume is several hundred times greater than that of the earth, being displaced and completely changing their form in the space of a few minutes.

22. It is hoped that the preceding sketch of the brilliant discoveries which have been recently made in astronomy by means of spectrum analysis will be serviceable to the student, in introducing him to this interesting branch of scientific investigation, and inducing him to read the original records of the observers who have so successfully prosecuted it.*

* These are contained in ever-increasing numbers in the publications and transactions of different learned societies, and space utterly fails to call attention to any in particular. Indeed so greatly has this branch of astronomy been extended since the above Appendix was written that it has almost become a science of itself, and has had several whole works devoted to it, amongst which we may specially name Schellen's "Die Spectralanalyse," translated by the Misses Lassell, daughters of the late great astronomer.

After much consideration we have thought it best to leave practically untouched Mr. Main's clear exposition of the first principles of the subject, and not enter upon its later developments, which are scarcely suited to the elementary character of this little work. We may just mention, however, that Dr. Huggins has extended his investigations into the motions of approach and recession of other stars besides Sirius, and that his results have been essentially confirmed by the observations made at Greenwich by the present Astronomer Royal, Mr. Christie, and by Mr. Maunder, Superintendent of the Physical Department at the Royal Observatory.—Ed.

THE END.

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SUPPLEMENTARY NOTE.

WHILST these revised sheets were passing through the press, two more small planets were discovered; the first by Dr. Palisa, at Vienna, on July 19th; the second by M. Paul Henry, at Paris, on August 12th. Besides our Earth, there are now known, therefore, eight large, and two hundred and twenty-seven small, primary planets; besides our Moon, nineteen satellites or secondary planets, revolving round five of the former.

A total eclipse of the Sun was observed in Egypt on the 17th of May, and further interesting observations were made bearing on the nature of the so-called corona which is seen to surround the Sun on these occasions. A very interesting circumstance of that eclipse was the discovery of a comet seen close to the Sun, whilst totally eclipsed, which had not been observed before, and has not been seen since.

Great attention is of course now being directed to the approaching transit of Venus on the 6th of next December, preparations being nearly completed for observing it by the astronomers of different countries. Only the ingress and the first part of the transit will be visible in England; the whole transit will be visible over nearly the whole of the American continent. When the observations are collected, discussed, and compared with those made in 1874, it will probably be possible to obtain a more accurate determination of the Sun's parallax and distance than has yet been made. No other transit of Venus will occur until June 8th, 2004.

W. T. L.

Blackheath, August 17th, 1882.

*** As some of our readers may wish for a more detailed account of astronomical instruments and their modes of use than Mr. Main's space allowed him to give, we may refer them to Mr. Heather's work on "Surveying and Astronomical Instruments," forming No. 170 of this series of Rudimentary Treatises.

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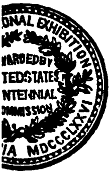

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